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The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

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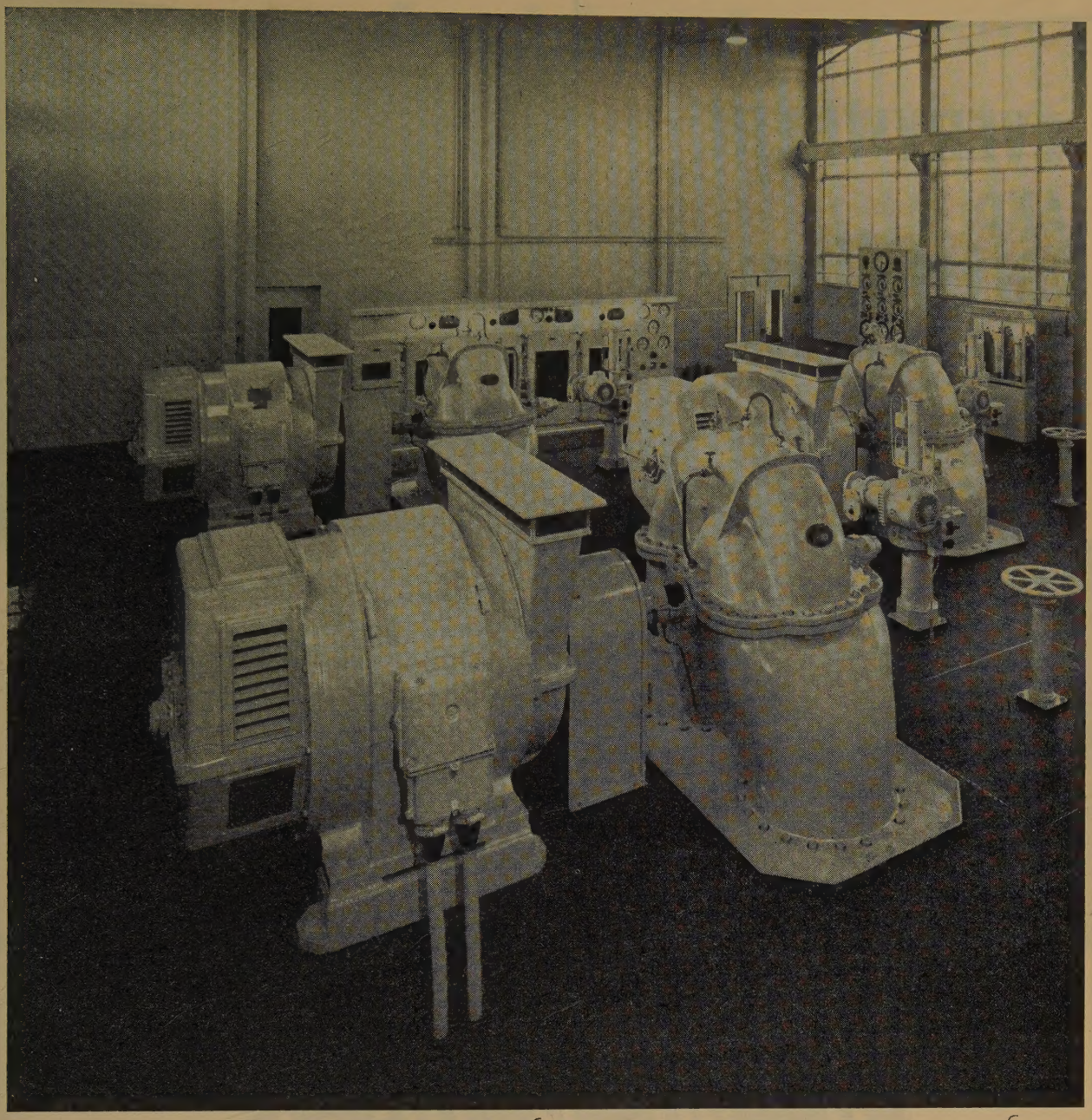
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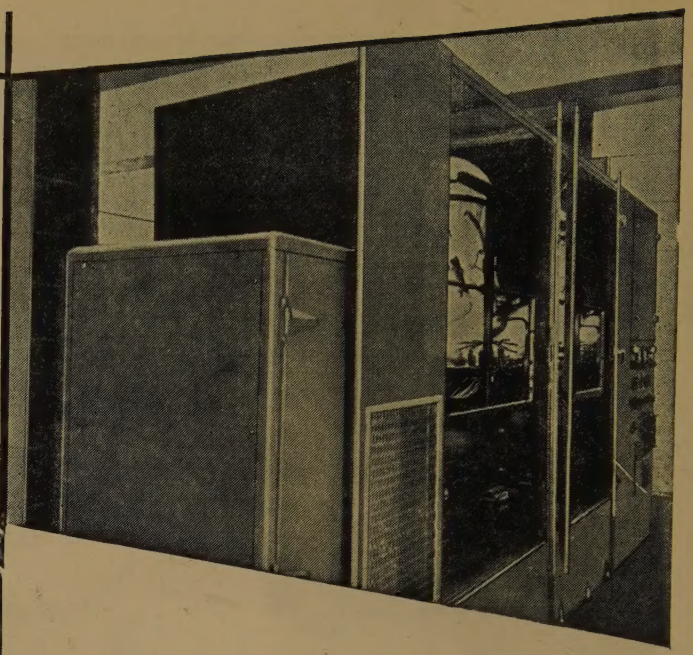
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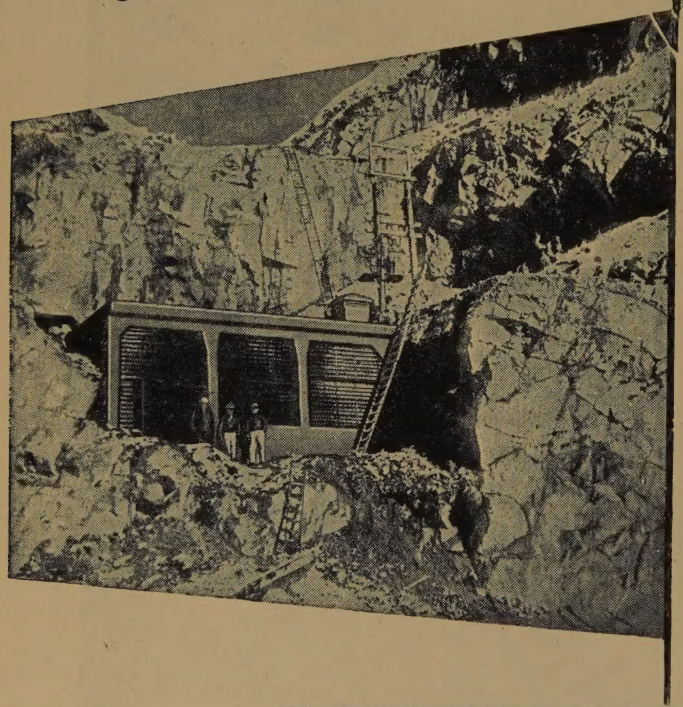
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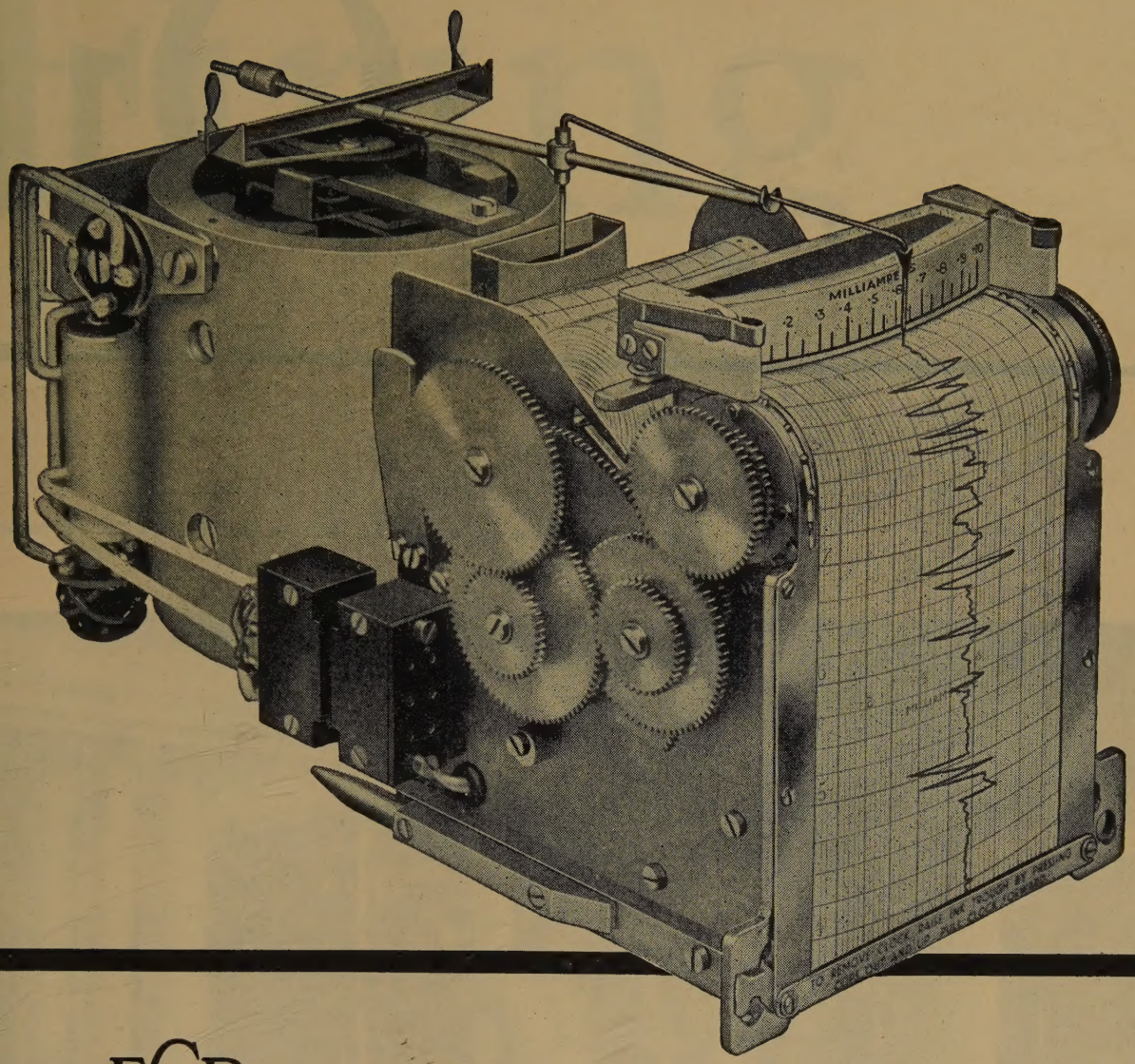
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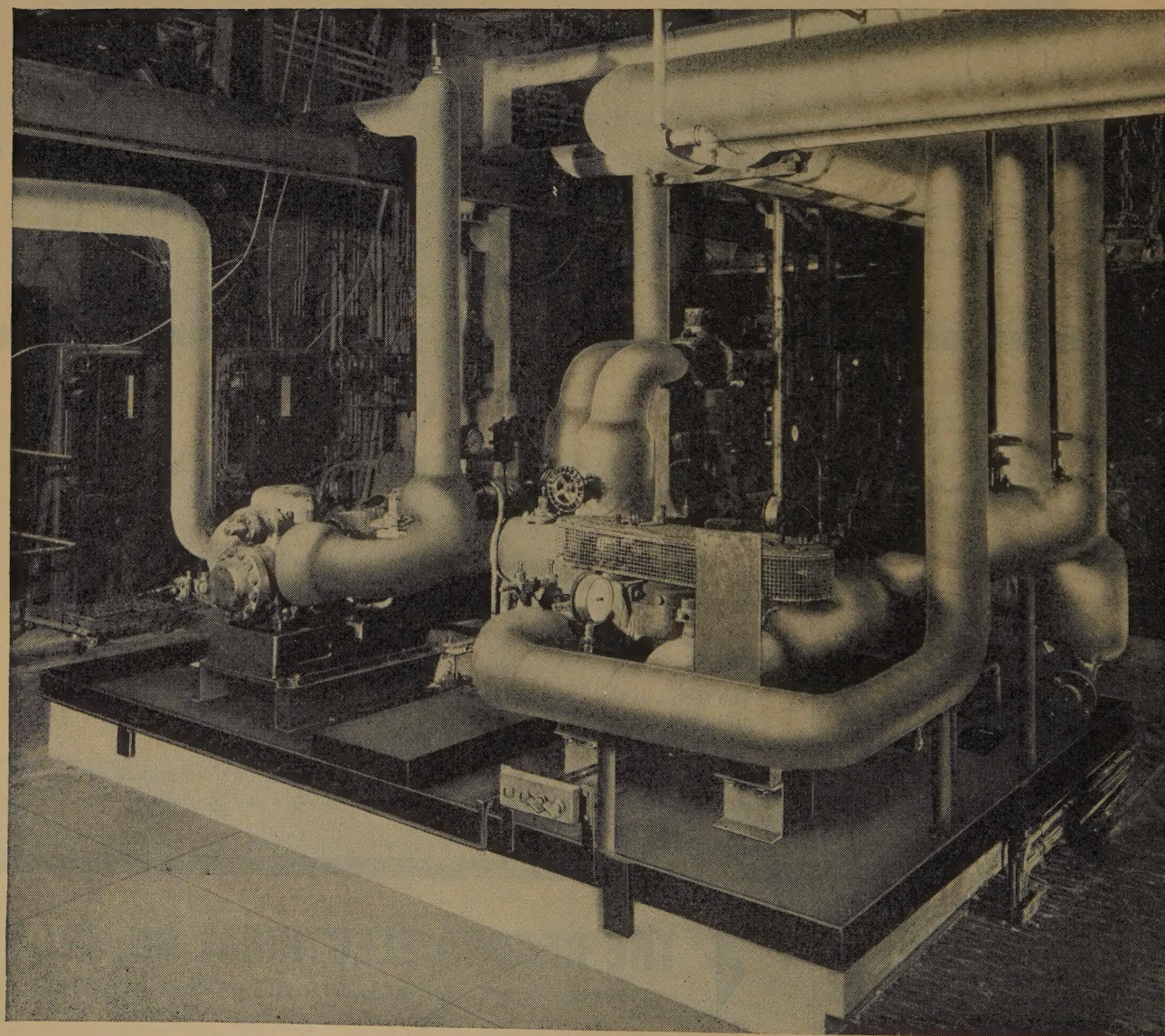
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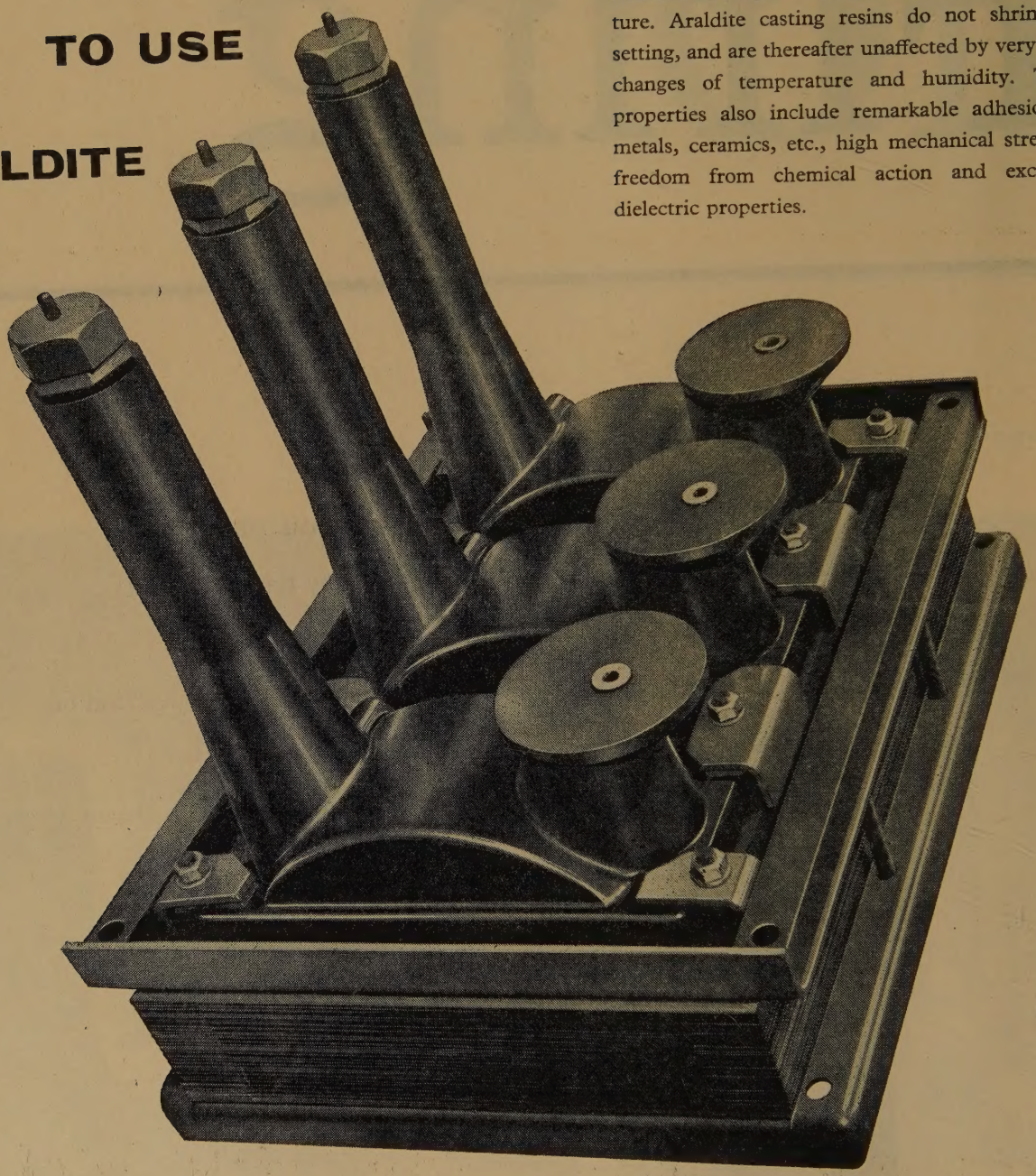
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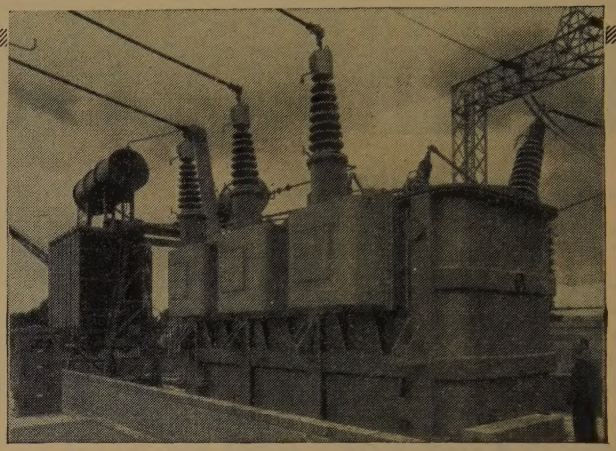
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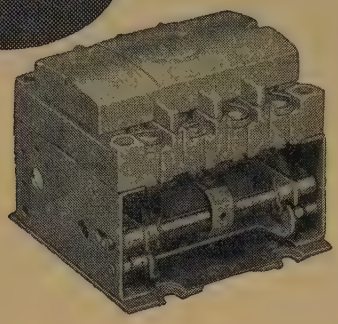
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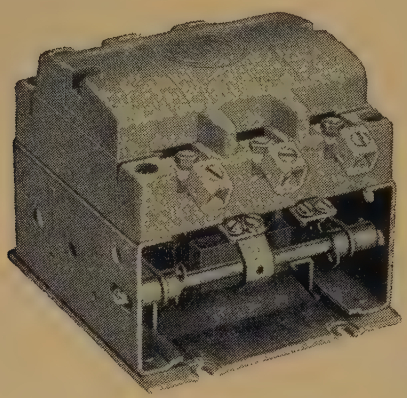
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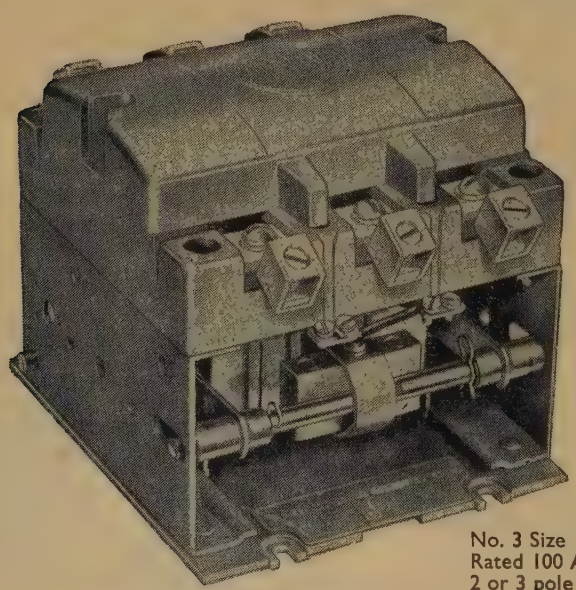
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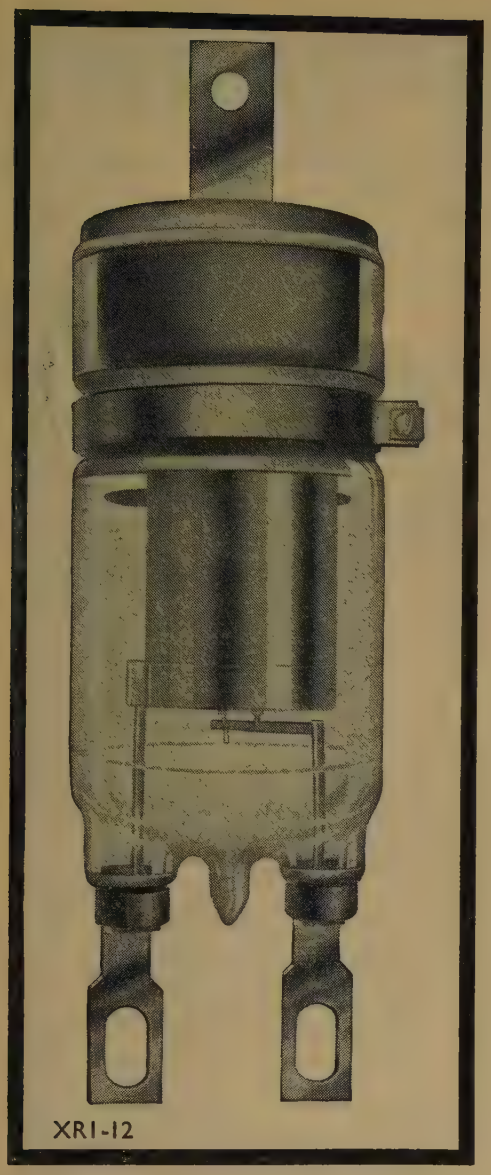
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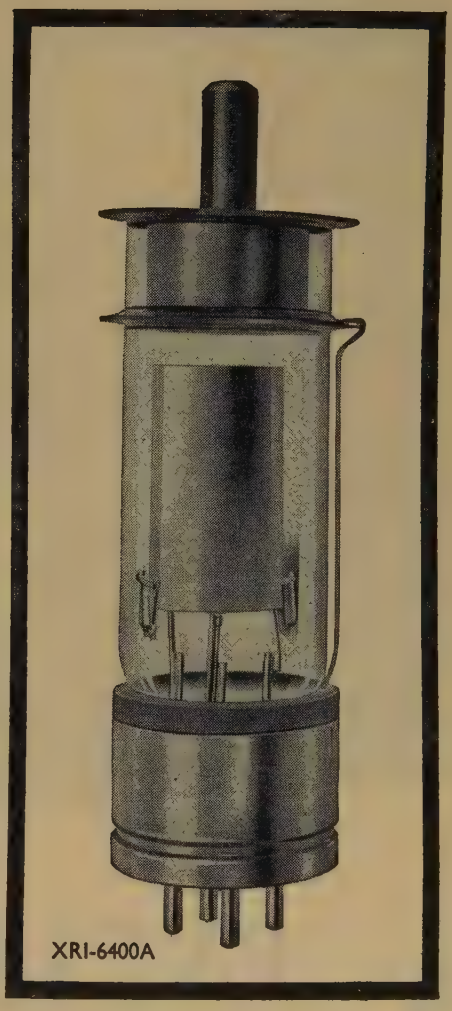
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6 and 12 amp Xenon Triode Thyratrons

New Disc-Seal construction gives these positive advantages

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XR1–6400A	6807	2.5	21	1.5	1.5	80	6.4	60
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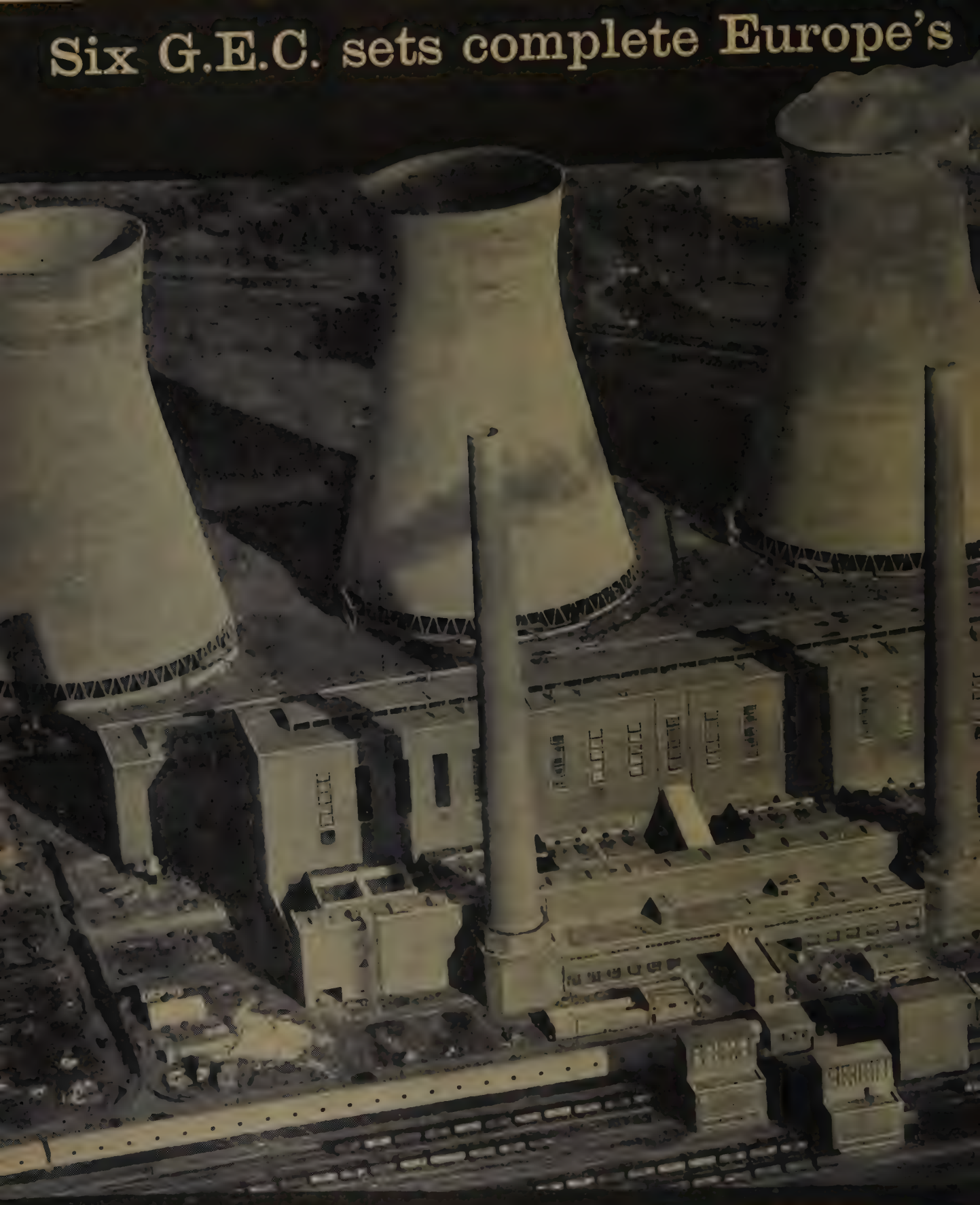
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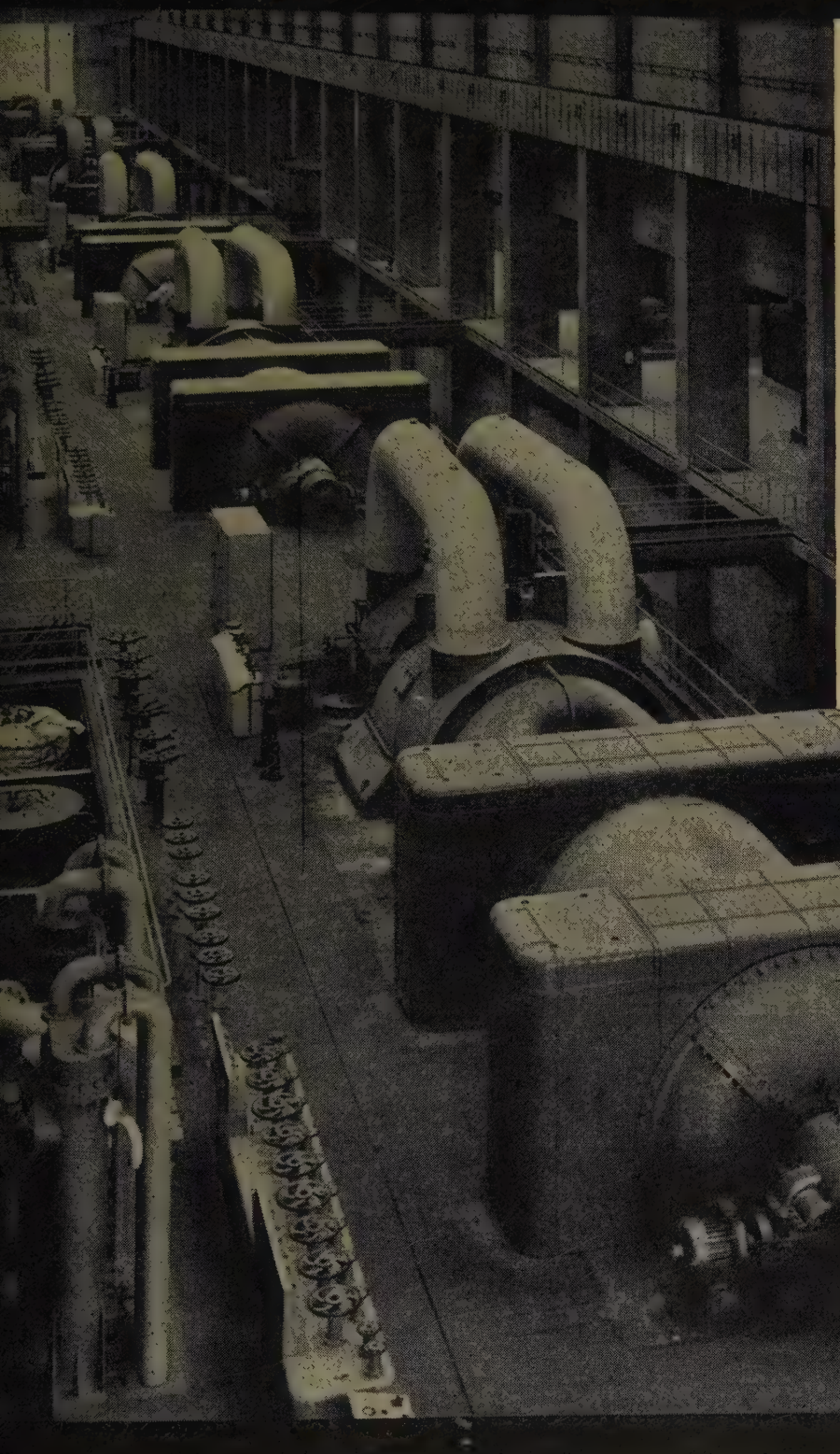
Six G.E.C. sets complete Europe's



Aerial view looking north of Hams Hall 'C'

G.E.C.

largest power concentration



Six G.E.C. 60 MW hydrogen-cooled turbo-generators have been erected and installed at Hams Hall 'C' for the Midlands Division of the Central Electricity Generating Board.

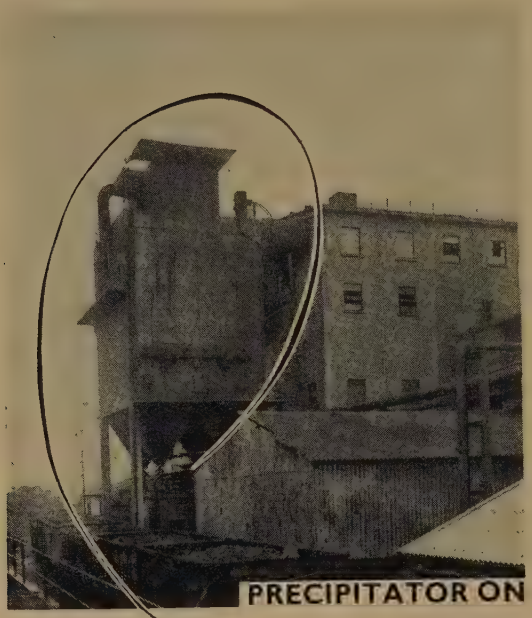
All machines from No. 1 to No. 6 were commissioned in less than two years. Steam conditions:— 900 p.s.i.g. 900° F.

The group — comprising Halls 'A', 'B' and 'C' — is now complete. Hams Hall 'C' brings the total installed capacity of Europe's largest power concentration up to 930 MW.

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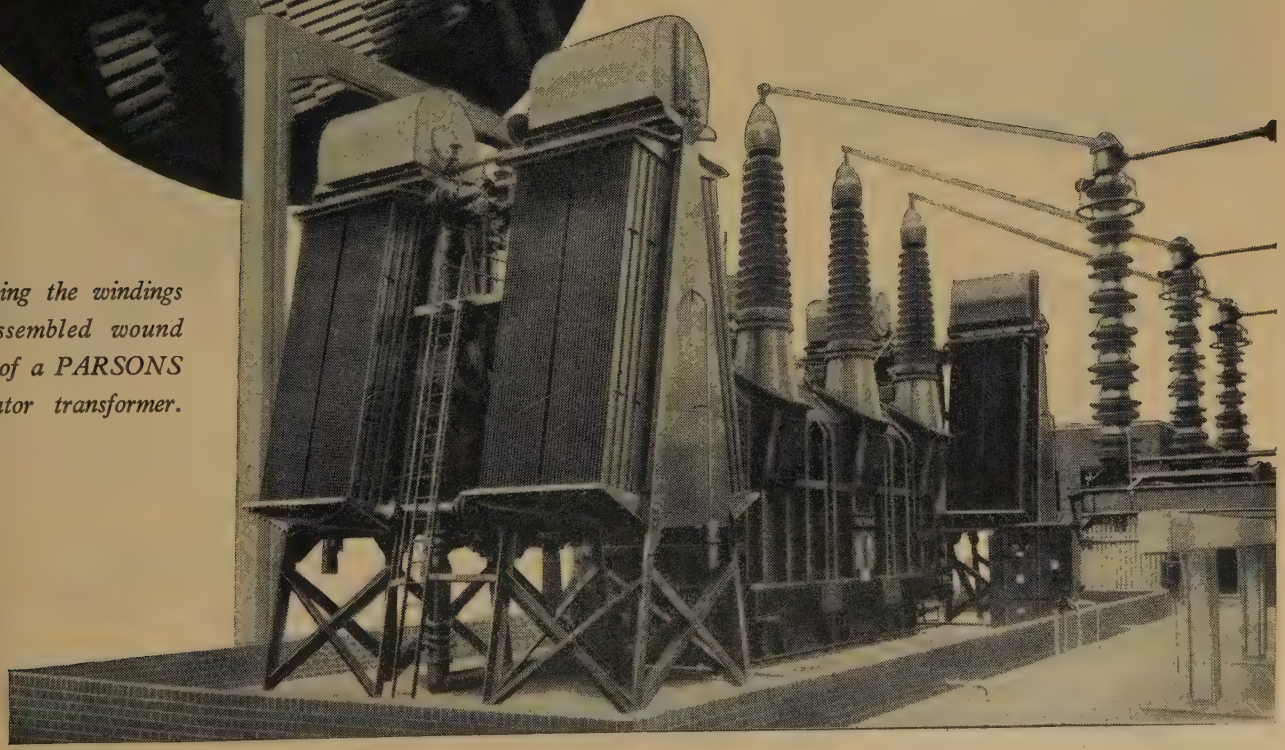


components of power

All over the world PARSONS have supplied all types of oil immersed distribution and power transformers, from 5 kVA up to the largest units for extra-high voltage. A 210 MVA three-phase generator transformer, for direct connection to the 275 kV super grid system of this country, is now under construction for West Thurrock.

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Checking the windings on assembled wound cores of a PARSONS generator transformer.

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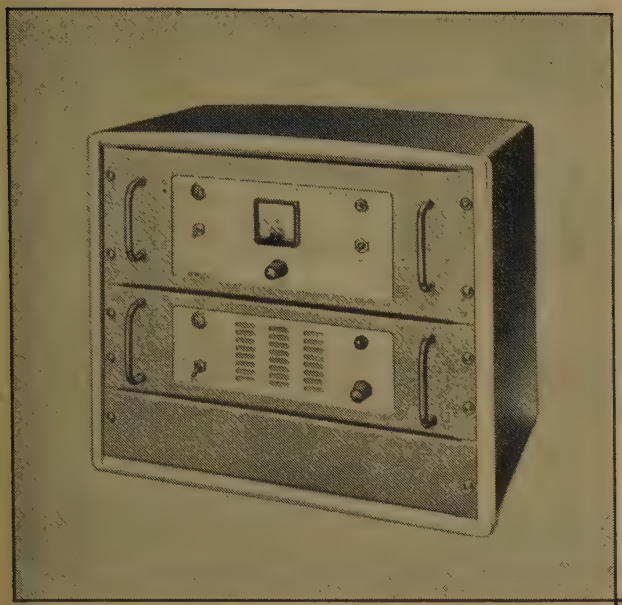
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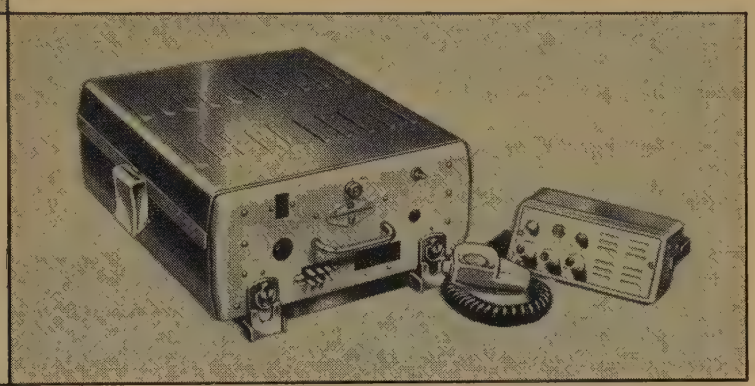
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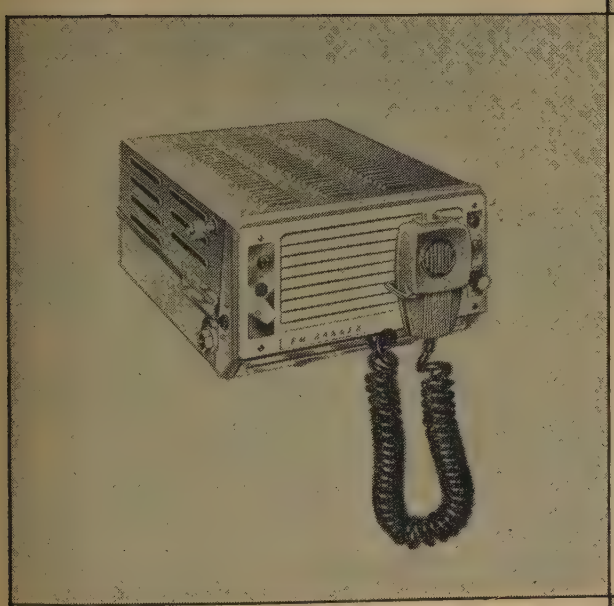


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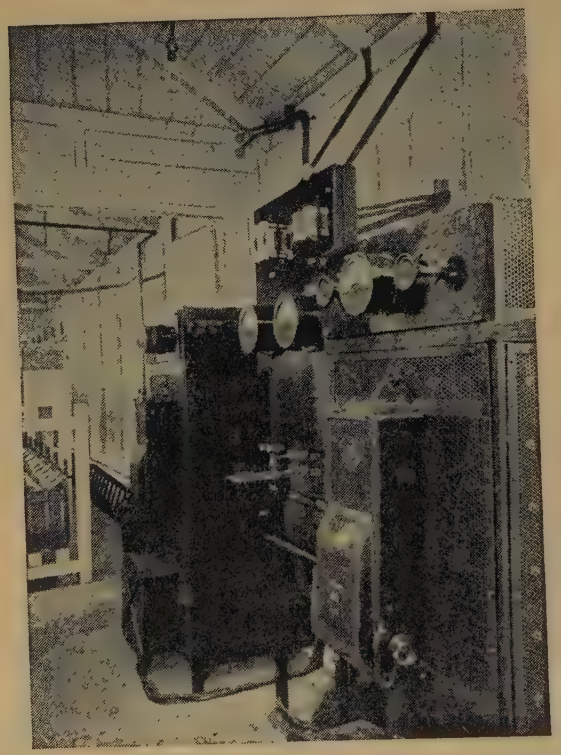
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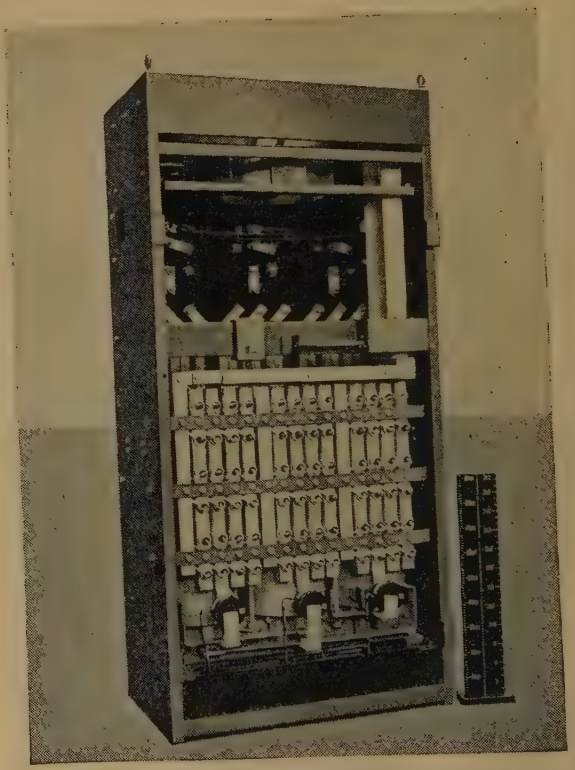
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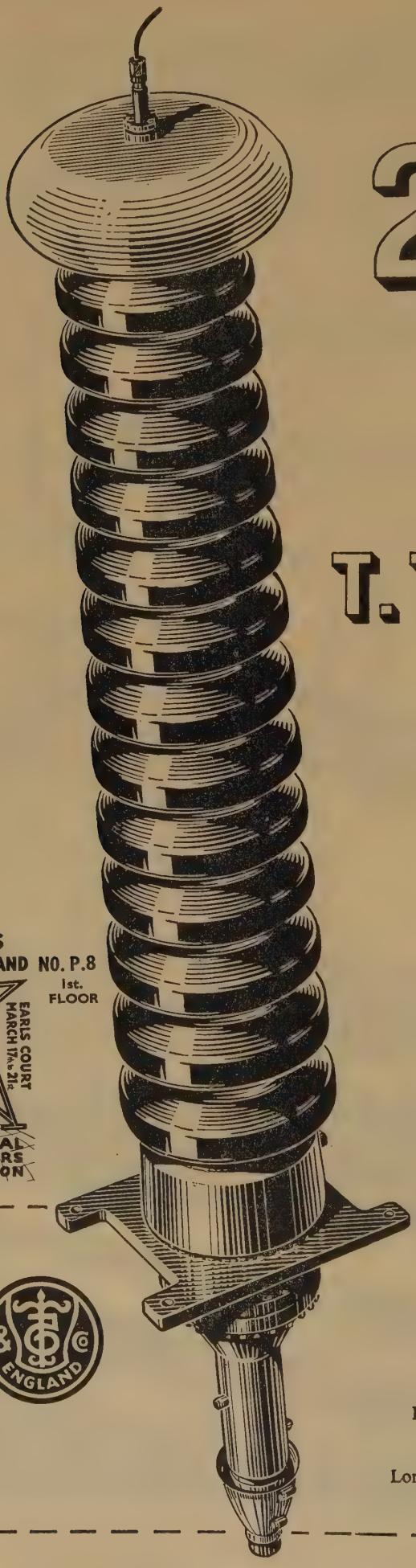
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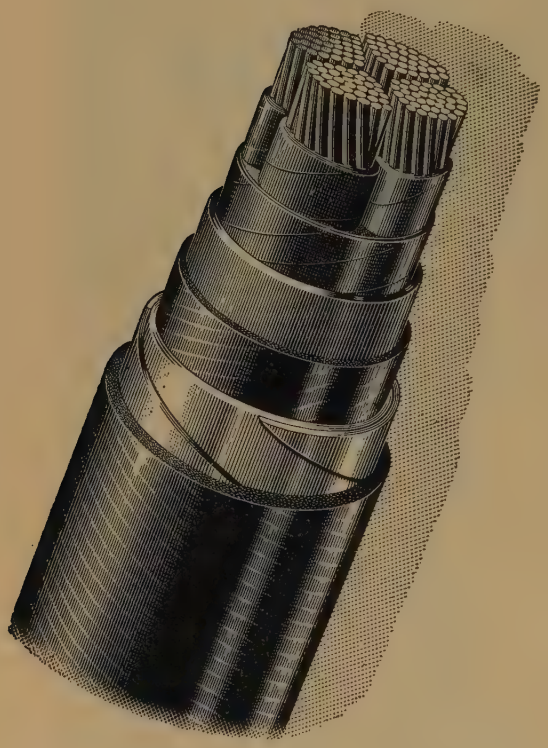


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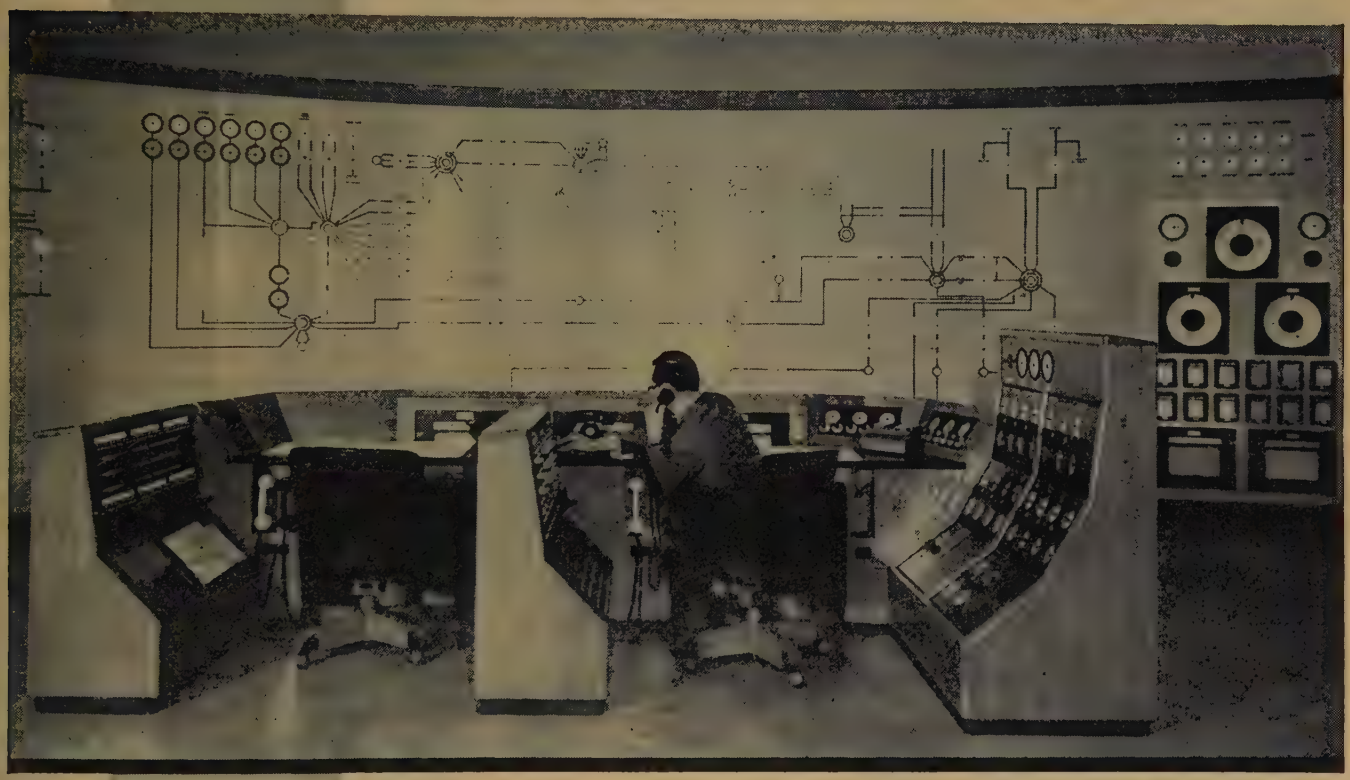
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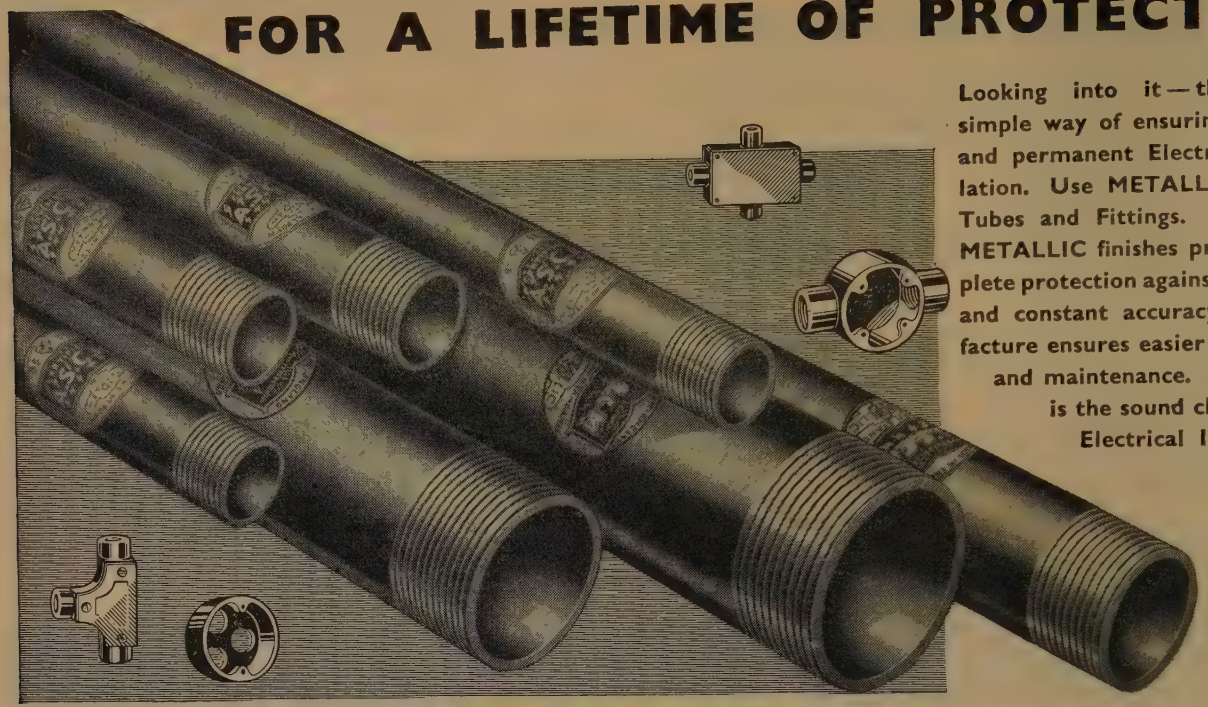
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HUNCOAT	No. 4	25 GRAINS	1·6 GRAINS
CHADDERTON 'B'	No. 2	20 GRAINS	5·6 GRAINS
CHADDERTON 'B'	No. 4	20 GRAINS	13·3 GRAINS
FLEETWOOD	No. 2	25 GRAINS	6·4 GRAINS
FLEETWOOD	No. 3	25 GRAINS	2·7 GRAINS
HACKNEY 'B'	No. 3	15 GRAINS	9·2 GRAINS *
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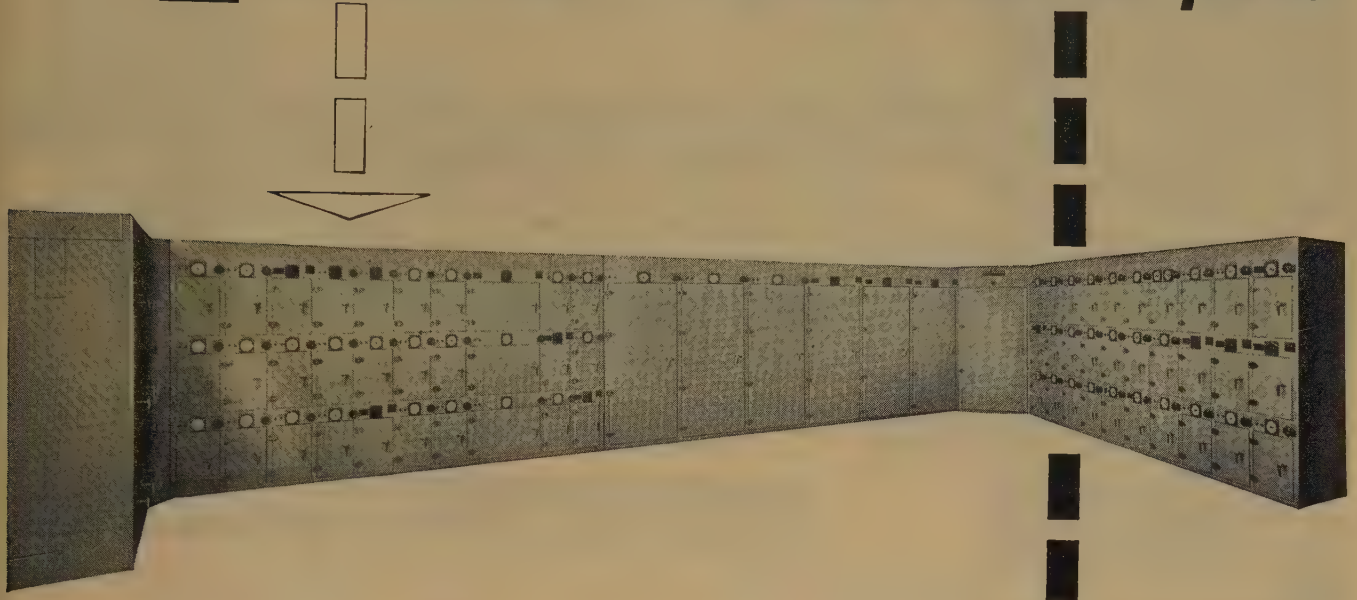
HIGH EFFICIENCY ELECTRO-PRECIPITATION BY *Simon-Carves Ltd*

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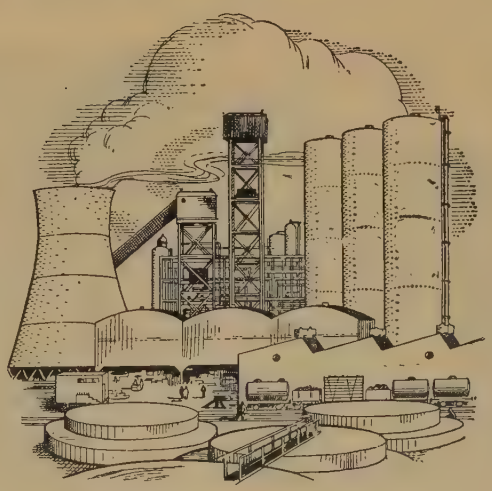
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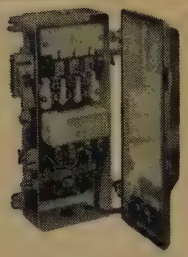
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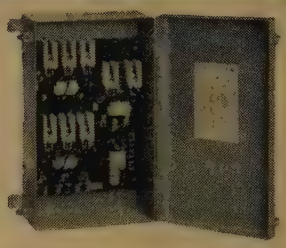
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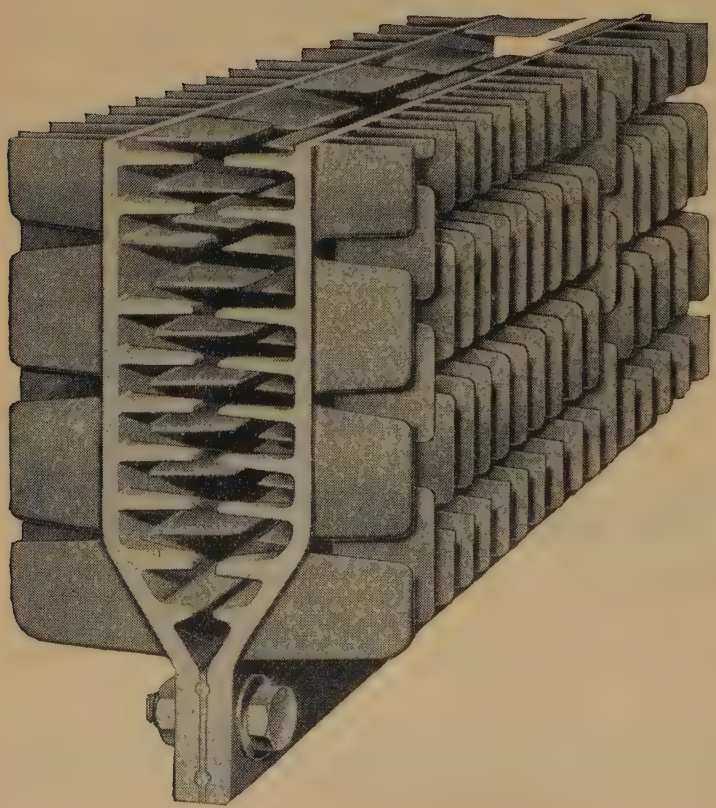


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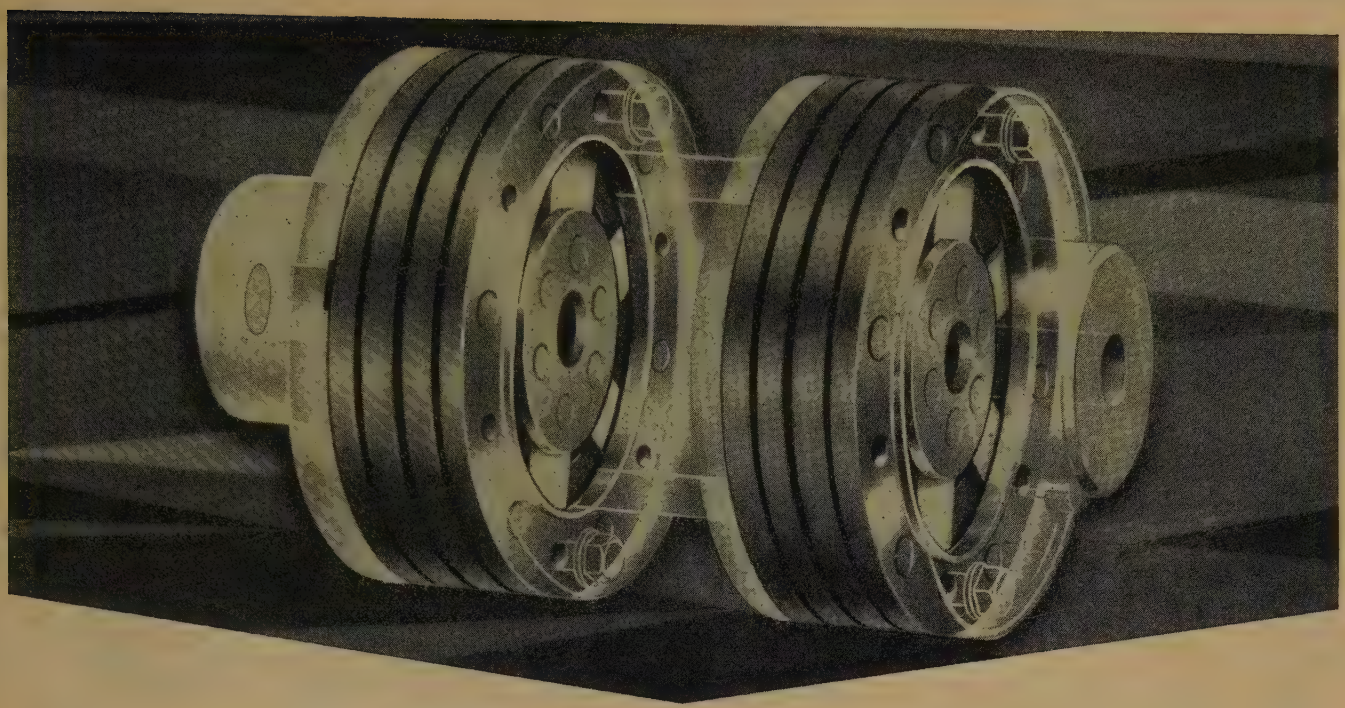
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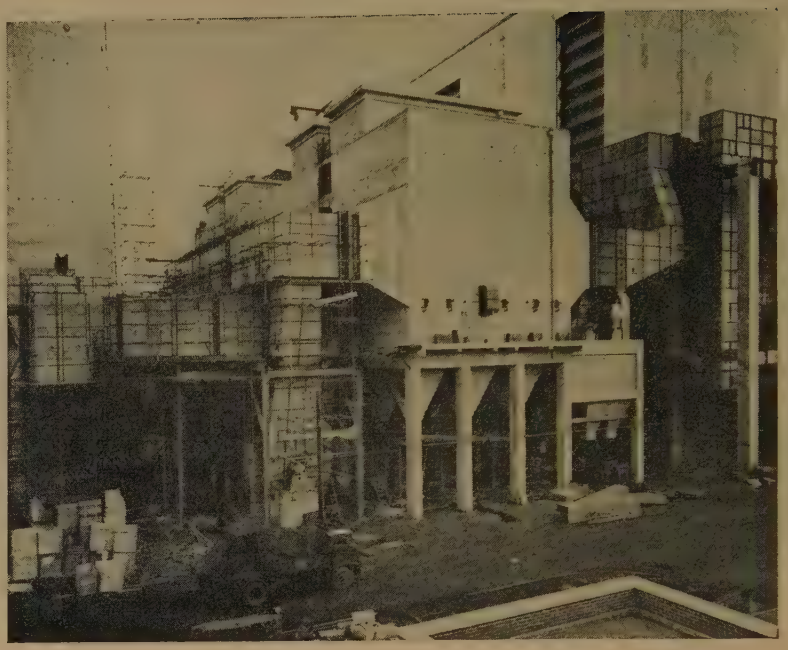
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PRECIPITATORS

ALL FOUR BOILERS OF BLYTH 'A.' POWER STATION WILL BE EQUIPPED WITH LODGE-COTTRELL PRECIPITATORS: AND THE FIRST TWO BOILERS OF BLYTH 'B.'

THIS PHOTOGRAPH SHOWS THE RE-INFORCED CONCRETE CASING FOR THE PRECIPITATORS FOR THE FIRST TWO BOILERS OF 'A.' STATION.



With Acknowledgments to: Central Electricity Generating Board. Messrs. Babcock & Wilcox & Co. Ltd. Messrs. Merz & McLellan. Messrs. Yarrow & Co. Ltd.

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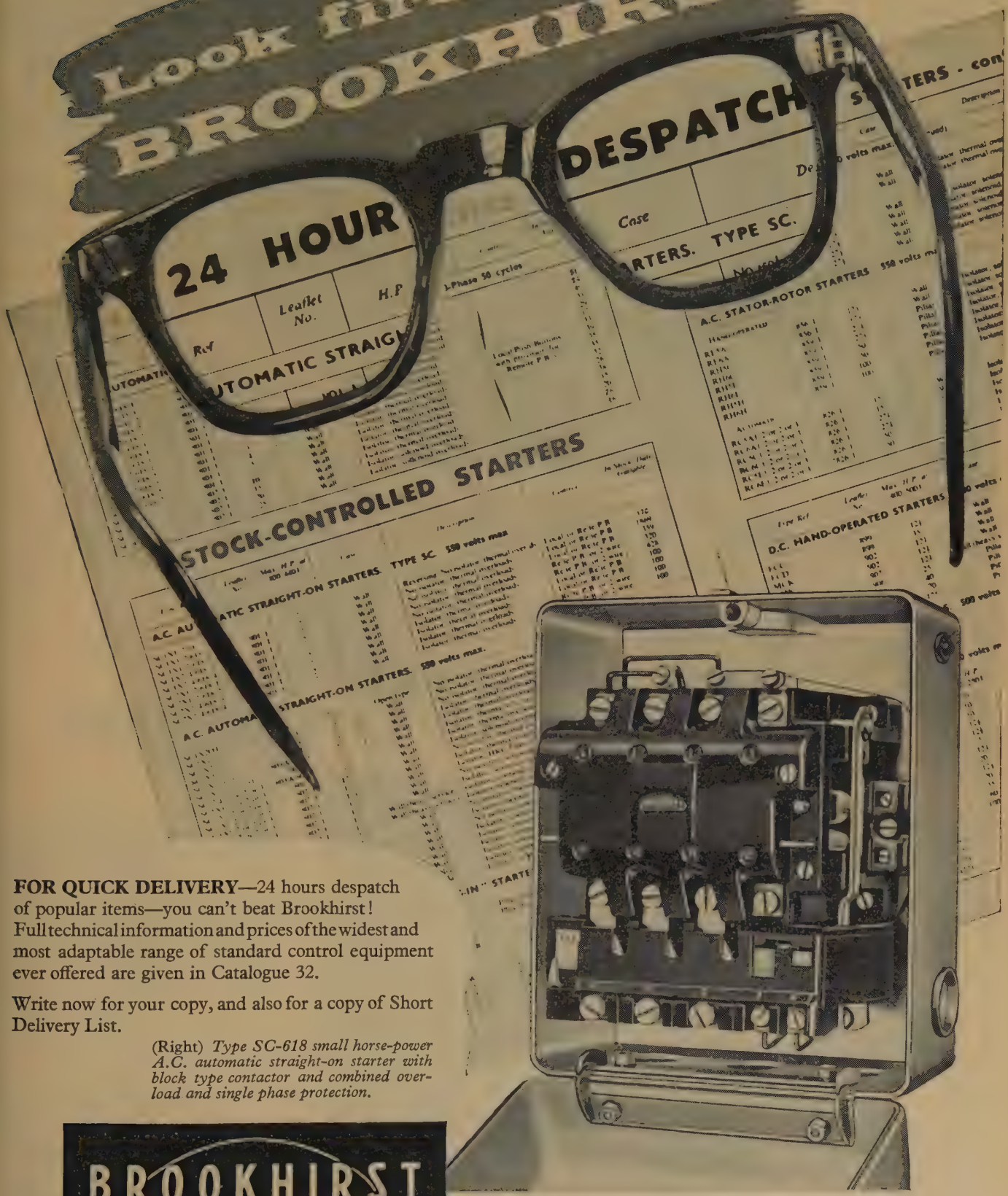
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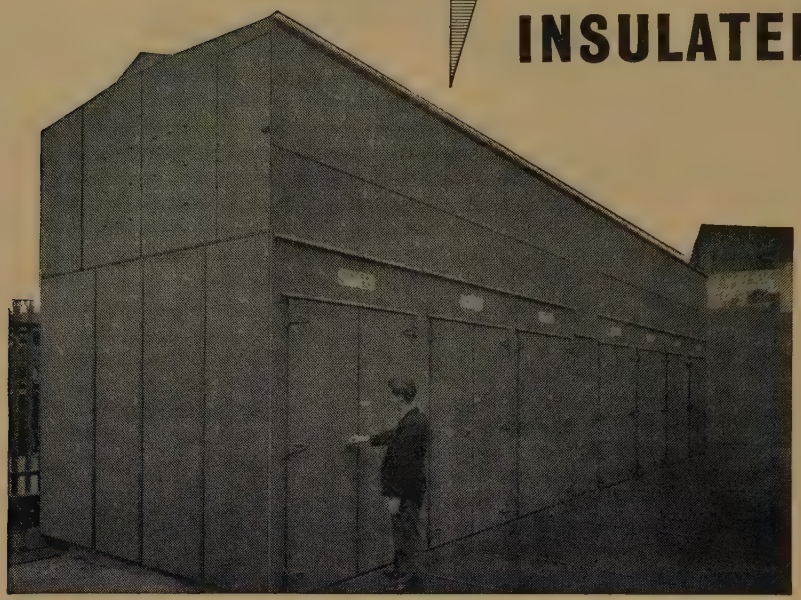
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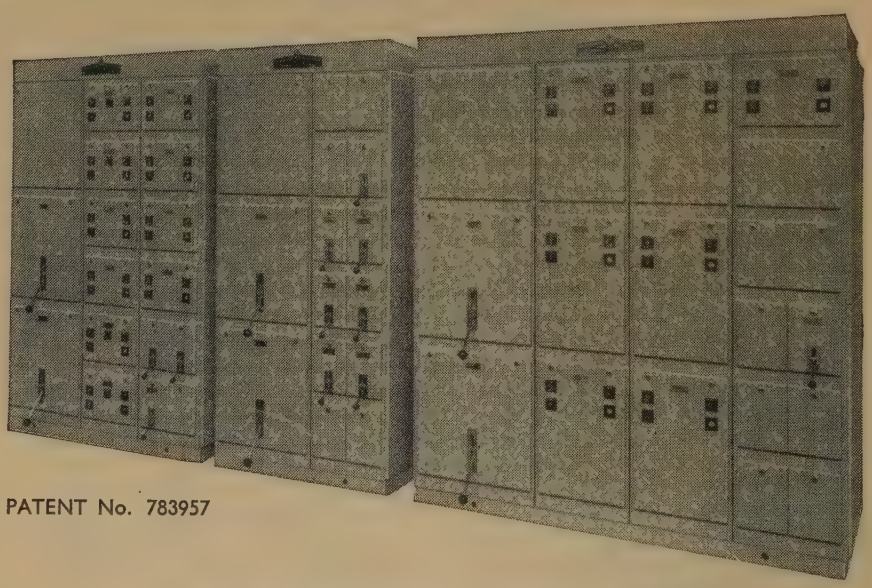
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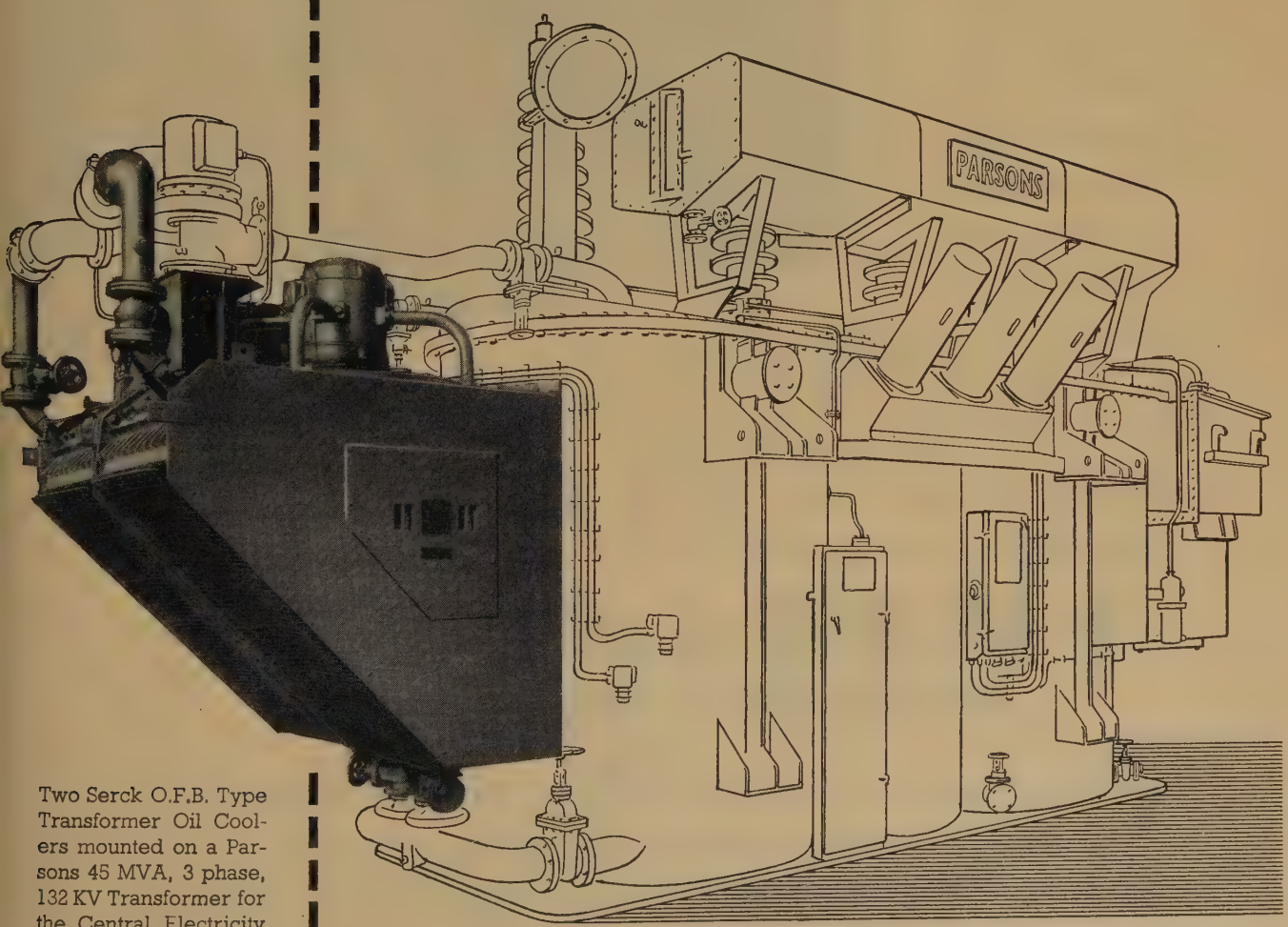
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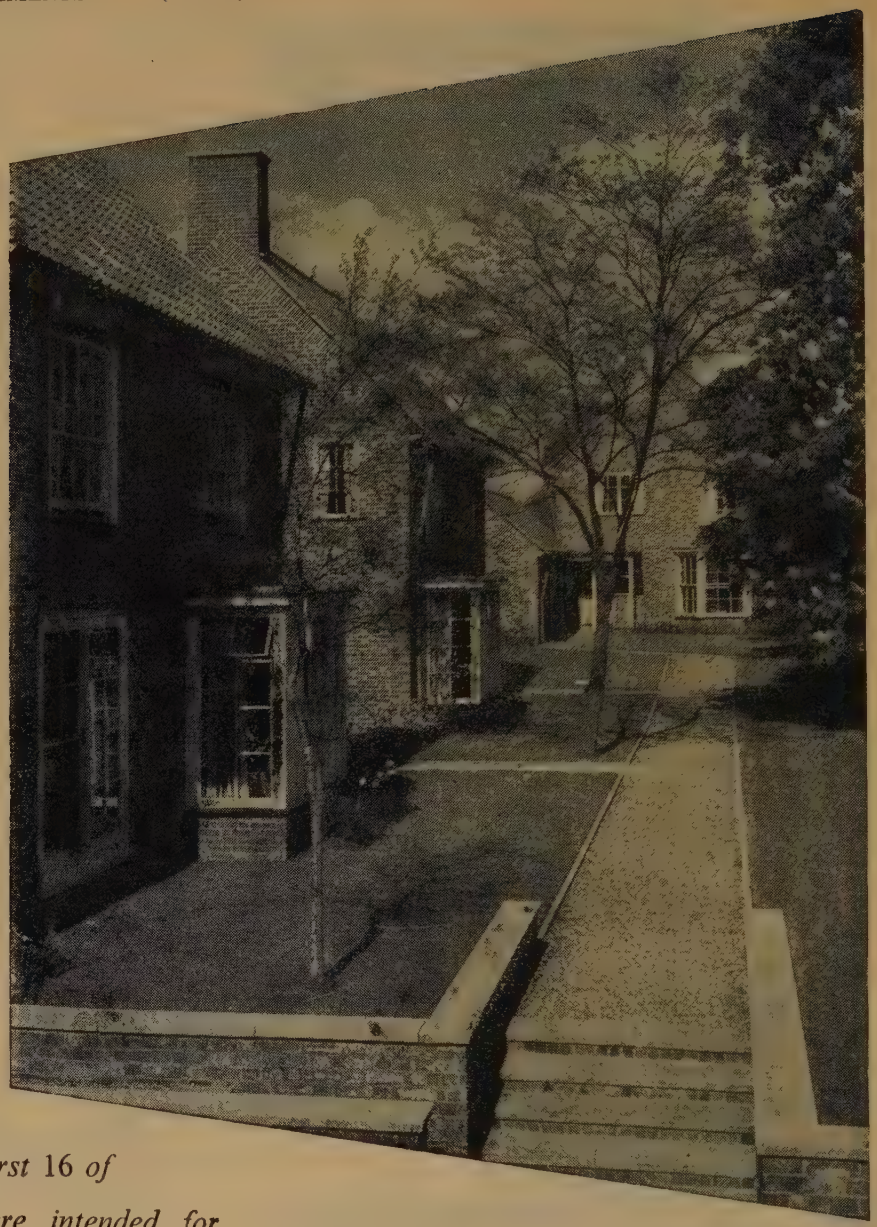


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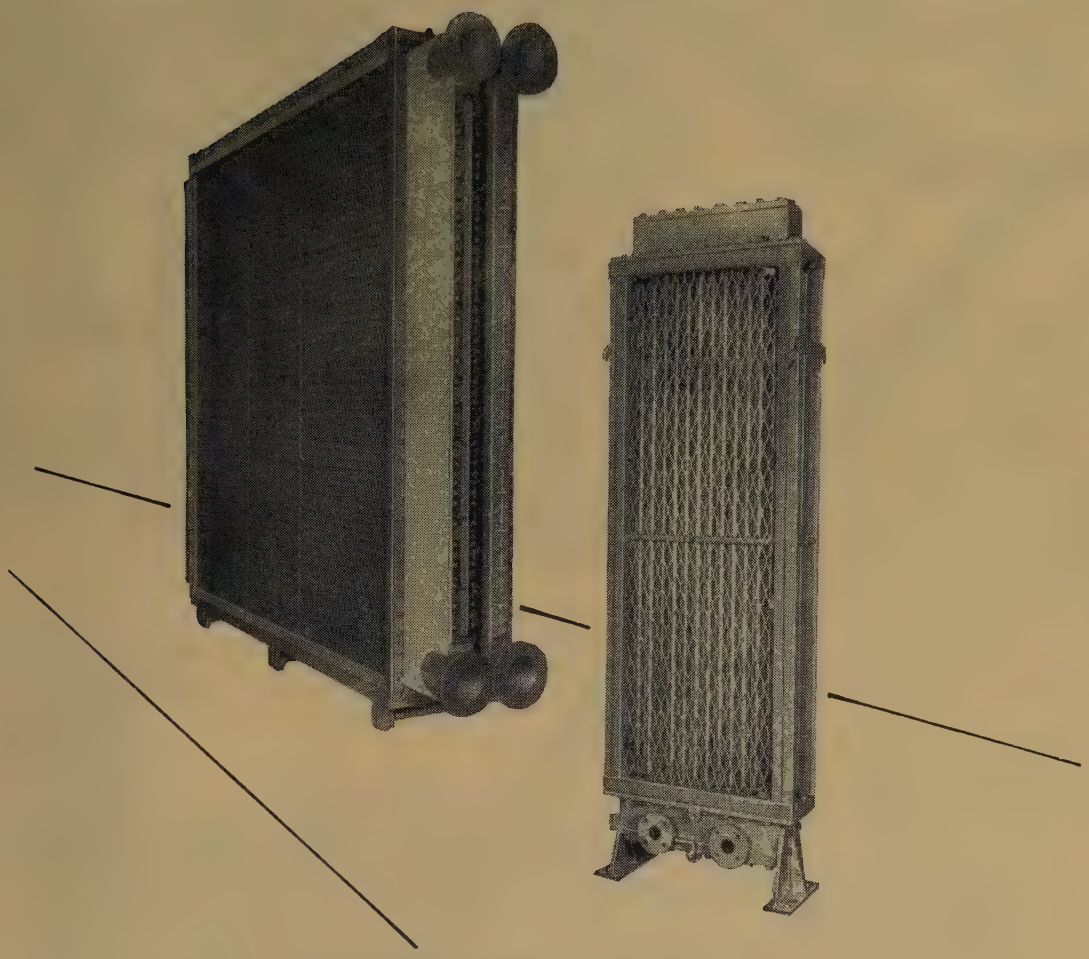


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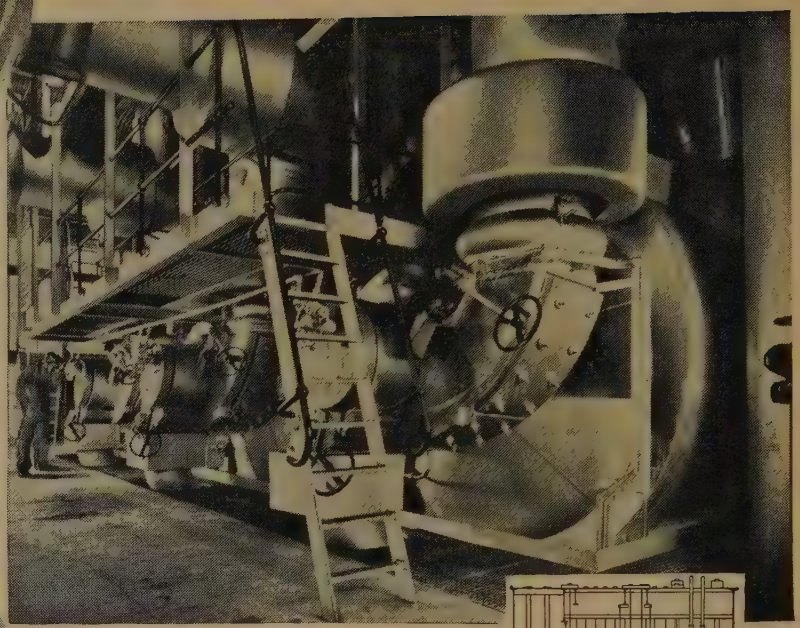
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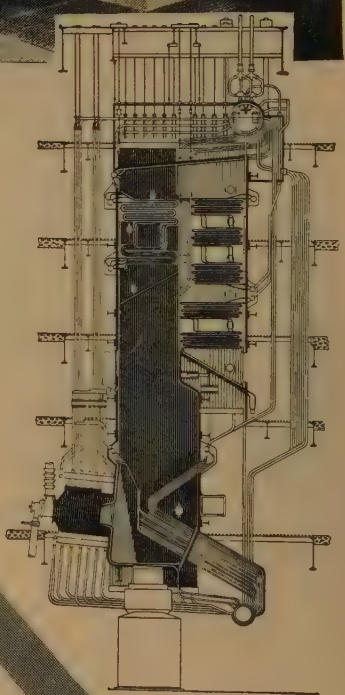
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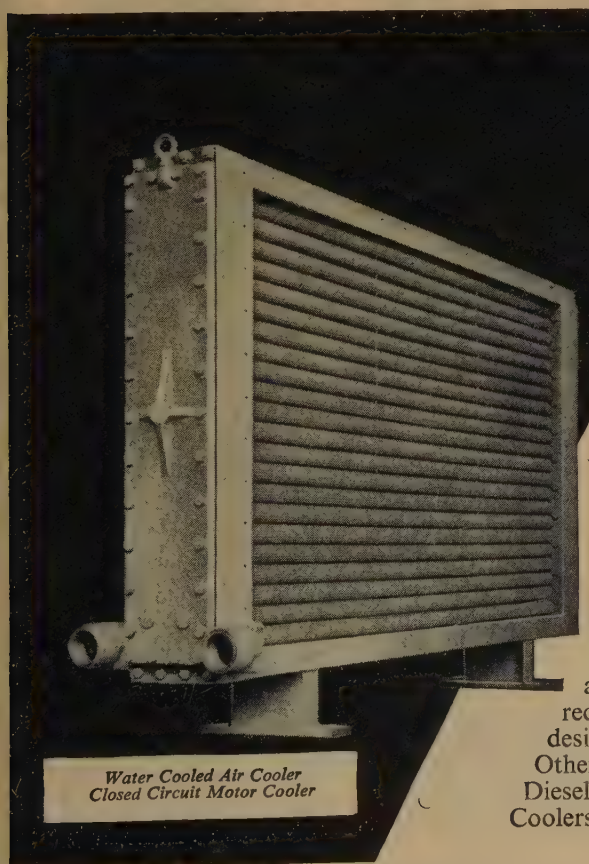
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INDEX OF ADVERTISERS

Firm	page
Airmec Ltd.	
Aberdare Cables Ltd.	xxiv
Aluminium Wire & Cable Co. Ltd.	
Arrow Electric Switches Ltd.	x
Babcock and Wilcox Ltd.	xxxviii
British Thomson-Houston Co. Ltd.	viii
Brookhirst Switchgear Ltd.	xxxi
Cable Makers Association	ix
Chamberlain and Hookham Ltd.	xxx
Ciba (A.R.L.) Ltd.	vi
Dewhurst and Partners Ltd.	xxvii
Donovan Electrical Co. Ltd.	xxviii
Electro Mechanical Mnfg. Co. Ltd.	xxxii
English Electric Company Ltd.	xii
Ferguson Pailin Ltd.	
Ferranti Ltd.	xxxiii
General Electric Co. Ltd. (Erith Witton Turbo)	xiv & xv
General Electric Co. Ltd. (Telecommunications)	xxv
W. T. Glover & Co. Ltd.	
E. Green & Son Ltd.	xxviii
Hackbridge & Hewittic Elec. Co. Ltd.	ii
Heenan & Froude Ltd.	xxxvii
W. T. Henley's Telegraph Works Co. Ltd.	xl
International Combustion Ltd.	iv & v
Isopad Ltd.	
Laurence, Scott & Electromotors Ltd.	i
Lodge-Cottrell Ltd.	xxx
Lodge Plugs Ltd.	
M. and C. Switchgear Ltd.	
Mersey Cable Works Ltd.	xxi
Metaducts Ltd.	xxix
Metallic Seamless Tube Co. Ltd.	xxvi
Metropolitan Vickers Elec. Co. Ltd.	
Mullard Ltd. (Valves)	xi
Nalder Bros. & Thompson Ltd.	xiii
C. A. Parsons & Co. Ltd.	xvii
Pye Telecommunications Ltd.	xix
Record Electrical Co. Ltd.	iii
A. Reyrolle & Co. Ltd.	xxiii
Richard Johnson & Nephew Ltd.	xxiv
Richard Thomas & Baldwins Ltd.	
Serck Radiators Ltd.	xxxv
Simon-Carves Ltd.	xxvi
South Wales Switchgear Ltd.	xxxii
Spiral Tube & Components Co. Ltd.	xxxix
Standard Telephones and Cables Ltd.	
Sterling Varnish Co. Ltd.	
Sturtevant Engineering Co. Ltd.	xvi
Taylor Tunnicliff & Co. Ltd.	xxii
Thomas Bolton & Sons Ltd.	vii
Wakefield-Dick Industrial Oils Ltd.	xviii
G. and J. Weir Ltd.	
Westinghouse Brake and Signal Co. Ltd.	xx
Zenith Electric Co. Ltd.	xxx



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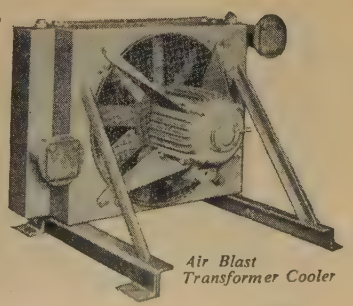
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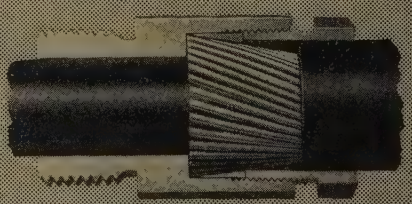
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VOL. 106. PART A. NO. 25. FEBRUARY 1959

The Institution of Electrical Engineers
Paper No. 2767
Oct. 1958
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INAUGURAL ADDRESS

By S. E. GOODALL, M.Sc.(Eng.), F.Q.M.C., President.

'ELECTRIC CABLES'

(*Address delivered before* THE INSTITUTION *9th October*, 1958.)

At this moment in the career of a newly-elected President of our great Institution, he stands before his friends with feelings so complex that they are not easy to analyse: trepidation is offset to greater or lesser extent by self-confidence; sense of great responsibility by sure knowledge of the support which will be afforded by colleagues, in particular by the immediate Past-President, and sense of inadequacy by determination to do one's best. All these, and more, I am sure my predecessors have felt before me, and I doubt not my successors in office will share them in due course.

I can only express my very sincere appreciation of the signal honour conferred upon me, and assure you that, despite my obvious deficiencies, I will do my utmost in the year ahead to uphold the high traditions and standards established by the many distinguished men who have done so much for our corporate body in previous years. It is a very real privilege to have one's name included in such a list. Quite apart from their technical and professional ability, they share one distinction in common: they have been and are always ready to encourage and help the younger man. This is a tradition which is among the finest cherished by our Institution.

This is not the first occasion on which the electric cable industry has been honoured by the selection of one of its members as President. Moreover, it is not the first occasion on which such selection has been made from the company with which I am associated, and I shall, I trust, be forgiven for a feeling of some pride in this fact.

As it happens, none of these gentlemen took as the subject of his Presidential Address a review of the past achievements, present state of development and future prospects of electric cable making. Reminding myself very firmly of the old and well-known adage, 'Fools rush in where angels fear to tread', I propose to attempt such a review. I believe that a useful purpose may be served if only by the demonstration of the enormous complexity of the technical and other problems that confront the industry to-day, due, in no small measure, to the machinations of such curious bedfellows as chemists and politicians.

Last year on this occasion we were treated to a masterly exposition of the incredibly rapid growth of one of our modern branches of industry—that connected with radio valves. Mr. Goldup chose as his significant date 1904. I make no apology for choosing a somewhat earlier date as my reference point, namely 1812. For it was in that year that Sommering and Schilling conducted a series of experiments in which a soluble material, said to be indiarubber, was first used for insulating wire, following a suggestion made by a Spaniard, named Salva, in 1795 concerning the feasibility of submarine telegraphy. Curiously enough, this first 'cable' developed by Sommering and Schilling was in a sense a power cable as the objective was the detonation of mines. For at least another 50 years, however, practically all development was to be concerned with telegraphy.

It is not my intention to attempt to provide anything like a complete history of the early days of cable making, but it may not be without interest to high-light a few of the more important early events, and, at the same time, to remind ourselves, albeit very briefly, of the concurrent political and social background.

As the 19th century began, we were still very largely living in rural communities. Communication and transport were difficult and slow, and the great drift from country to town had not begun. Some branches of industry were established, of course. For example, it has been estimated that there were 100 000 men and women, and 60 000 children, many of whom were very young, employed in the cotton mills. Such factory regions as there were formed a very small part of the whole, and many people were almost, if not wholly, unaware of the terrifying conditions that were developing, not only in the factories and mills themselves, but also in the slums which were springing up around them. There is no doubt that we have paid very bitterly in terms of mistrust and misunderstanding for many years for the callous misuse of human beings by our industrial forerunners. Despite this ugly blot, it would appear that, for the majority of the population, England was probably a very pleasant place. This was the heyday of the country craftsman, who justly held himself to be as good as any man. For the rich minority it must have been very pleasant indeed. English art was probably at its peak, as such names as Reynolds, Romney, Gainsborough,

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Sheraton, Hepplewhite, the Adam brothers, Capability Brown, and many others, will remind us. In literature and poetry also, great names will spring to mind. This was also the age of reform and revolt against the barbarous practices and customs of the times, so that the leading thinkers were beginning to arouse opinion against the cruelties of the day, even while new barbarities were being invented by many of the industrialists.

No account of this kind, however sketchy, can pass over the fateful year of 1831, in which Michael Faraday ennunciated and demonstrated the laws of electromagnetic induction, and thus made possible the generation and distribution of electrical energy. For the first time, it became apparent that cables would be required for such purposes, as well as for submarine telegraphic communication. Meanwhile, contemporary scientists and engineers were devoting a great deal of thought to the new technology of telegraphy, and schemes for achieving long-distance communication were receiving active consideration.

One of these developments is worthy of note. This was the Wheatstone and Cooke underground system for telegraphs, developed in 1837. It consisted of copper wires, supported at intervals in iron pipes by being laid in grooves in baulks of timber. An installation of this kind was laid in 1838 between Paddington and West Drayton for the Great Western Railway and operated successfully for at least seven years. This may be regarded as the forerunner, not only of the methods adopted by Crompton and others for power distribution, but also of the modern high-frequency coaxial cables used for long-distance telephony and television.

By the middle of the century a number of successful telegraph systems were operating in this country, developed and owned by telegraph companies. Practically all the lines were overhead, and where underground installations were adopted considerable trouble, due to ingress of moisture, had been experienced. Meanwhile, the newly discovered natural gum, known as gutta percha, had been introduced into this country and used for a variety of purposes, mostly domestic. The practical application of this material as a cable insulant was due to Werner Siemens in Germany, and his early trials led eventually to the widespread use of this material for both underground and submarine cables. It is believed by some that Faraday suggested this possible use of the material to his friend William Siemens, who sent a sample to his brother Werner. It is certain that a sample was so sent, and it is interesting to remember that Sir William was, some twenty-odd years later, to become our first President.

By 1851, the first cross-Channel telegraph cable was successfully laid. By this time also several manufacturing companies producing both telegraph instruments and cables were established, and two or three of these in fact were to survive as household names to this day.

Meanwhile, social conditions were changing considerably. Although landed interests were still dominant, industry was expanding at an enormous rate, and the railways, commenced in 1825, were now running 2000 miles of line. Factories, hitherto confined almost wholly to the north, were now appearing near London and other cities. The population of London, only 750000 at the start of the century, was now well over two million. The rich landowners, living in their great London houses, were challenged in wealth and power by the newly-enriched commercial magnates, while at the other extreme many lived in abject poverty in filthy slums, or shared the fate of the down and outs and homeless urchins, who slept in their thousands under the arches of the Adelphi or Waterloo Bridge. The import of cotton was now four times as large as in 1800, and accounted for nearly one-third of the whole trade of the nation. Legislation to limit hours and improve conditions in mills and factories was beginning to take shape, and very slowly some slight mitigation of the worst of the industrial evils was being achieved. Free trade had triumphed as a political doctrine; the threat of revolution was over, and the outlook for trade and industry was fair indeed.

It was against this background that Albert, the Prince Consort, pressed on with his idea for an exhibition of industry in London, which culminated in the opening of the Great Exhibition in Hyde Park by the young Queen Victoria in 1851. Then followed the magnificent achievement which was to establish British supremacy in submarine cable work for the next hundred years, and maybe more. After two tragic and expensive failures, it was in 1866 that a successful transatlantic cable was laid by a company formed primarily for that purpose. It is, I think, of particular interest to record that Sir John Dean, who is now Chairman of that same company, is a Member of the Council of this Institution, Moreover, as I am sure you realize, it is only a few years ago since he played a leading part in that epoch-making submarine cable success, namely the transatlantic telephone cable. With this project, of course, the name of our distinguished Past-President, Sir Gordon Radley, will always be associated.

By 1871, there were sufficient engineers in this country directly concerned with telegraphy to render it desirable for them to form a learned society of their own for the purpose of discussing their mutual technical and scientific problems. In that year, the Society of Telegraph Engineers was formed, and the first meeting took place in 1872. It is with pleasure and pride that I recall that among the list of original members is to be found the name of W. T. Henley. Fifty years later, in 1922, our membership had grown to 10000, and to-day, after a further 36 years, we number over 44000.

The first Presidential Address, given by Sir William Siemens, made considerable reference to the problems of line conductors and insulation. The first paper to make direct reference to submarine cables was communicated by Professor Fleeming-Jenkin, and was published in May, 1872. In 1873, a paper by G. E. Preece (the Secretary), entitled 'On Underground Telegraphs', was read and discussed. It was, however, during a debate held by the Society in February, 1876, that the English predominance in submarine telegraphy was emphasized by Sir William Siemens, who said, 'Submarine telegraphs are specifically English enterprises. I might go further, and say every submarine cable which is now working is, almost without exception, the produce of this country, and has been shipped from the Thames'.

Almost from the inception of the new Society, it became apparent that the interests of electrical engineers would not be restricted to telegraphy alone, and it is greatly to the credit of our founders that they had the foresight to welcome and encourage engineers and scientists concerned with other aspects of electrical work, so paving the way for our own broad conception of the field of electrical engineering. And so it was, in order to connote the extending scope of activity, that the name of the Society of Telegraph Engineers was altered by the addition of the words 'and of Electricians' in 1881. This change was to be considered adequate for only a few years, and in 1888 the Society was renamed 'The Institution of Electrical Engineers', a choice which has stood us in good stead for the last 70 years, and which we trust will continue to serve the needs of succeeding generations for many years to come.

Meanwhile, the use of electricity for lighting was beginning and attention was focused on the possibility of distributing power underground. At first only direct current was employed and low-voltage distribution was only possible up to short distances from the generating source. During this period, many of the systems developed did not use cables, but employed conductors

supported on insulators in ducts or trenches. Where cables as such were employed, rubber soon achieved recognition as one of the best insulating materials.

It was the pioneer work of the young Sebastian de Ferranti that really blazed the trial for the development of power cables as we understand them to-day. In 1887, as Chief Engineer of the newly-formed London Electricity Supply Corporation, at the advanced age of 22, he was responsible for the conception and design of the first large London power station at Deptford. This bold scheme broke new ground in many directions. It was the first successful demonstration of the advantage of high-voltage transmission, 10 000 volts being, according to contemporary opinion, both highly dangerous and impossibly difficult technically. Moreover, there were many opponents to the use of alternating current, and little, if any, faith in the newly-invented transformer. Not content, however, with overcoming all the practical and personal difficulties associated with such a venture, the young Ferranti was soon dissatisfied with existing types of cables, and designed and superintended the manufacture of an entirely new cable for his mains. In doing so, he produced the first high-voltage impregnated-paper power cable; a type which, although the subject of research and development and improvement over the years, has remained practically unchallenged for power purposes until the last few years. He also decided to employ a new type of construction, namely concentric conductors, and this point alone aroused a storm of criticism. It is, perhaps a sad reflection on our highly, and maybe over-, organized State to-day, that such a young genius would almost certainly find his ideas strangled by officials, committees, regulations and so on—those apparently indispensable features of the age in which we live.

By 1900, single-core and 3-core impregnated-paper lead-sheathed cables of several different designs were being supplied by several manufacturers, and demand was growing at a very rapid rate. This period is, of course, within the memory of some of our contemporaries, but, nevertheless, it may be of some interest to remind ourselves of one or two features of the time. General education was beginning to take effect. The school leaving age was raised to 14. The Board of Education was formed. Free elementary education had been made generally available only nine years earlier. Education, housing, transport, paving and, last but not least, street lighting, were now the responsibility of the newly-formed local authorities. Social responsibility, hitherto the prerogative of the minority, began to permeate public life. Public conscience and sense of responsibility was at long last aroused, and determined to enforce many belated reform measures.

In this atmosphere it was inevitable that such an industry as ours, uniquely equipped as it is to provide social services and amenities of many kinds, should flourish and expand, and as an essential component of the electrical industry, the cable making industry kept pace with this expansion.

Two of the earliest intruders into the telegraph monopoly were the electric light and the telephone. We have already seen how the demand for lighting created a need for cable development. The telephone, invented in 1876 by Alexander Graham Bell, soon posed an entirely new set of problems to the cable engineer. The necessary development was made very rapidly indeed, once the initial period of neglect of the basic principles had been passed.

Demonstrations have always been popular as enlivening features of our proceedings, and I am sure many of you shared with me the thrill of listening only a short while ago to the near-perfect reproduction in this lecture theatre of orchestral music coming to us from the United States over the transatlantic telephone cable. I was, however, reminded on that occasion of one of the first telephone demonstrations in this country. This was arranged by Sir William Preece in the lecture theatre of the Royal Institution one evening in March, 1878. He arranged to borrow a telephone line running between Southampton and London from the London and South Western Railway, and this was connected to a microphone in a room in Southampton and to a receiver in the Royal Institution lecture theatre. The idea was to hear in London a bugler playing 80 miles away. Alfred, Lord Tennyson was invited to listen and describe what he heard. After a few moments, he reported that he could hear nothing at all. This annoyed the lecturer who caught up the receiver and said that he could hear quite clearly 'The Campbells are Coming'. That he did so was quite remarkable, for the bugler had mistaken the date and did not turn up until the next evening.

Although cable manufacture for telephonic communication proceeded apace from about 1890, it was to be many years before telephone cable engineers understood and began to apply the brilliant theoretical work of Oliver Heaviside, published over the years 1885–1887. He set out quite clearly in his analysis of the problems of alternating-current transmission the significance of the four factors involved, namely capacitance, inductance, leakance and resistance. He stressed the importance of decreasing the resistance and increasing the inductance of lines if long-distance transmission was to be achieved within acceptable limits of distortion and attenuation. His emphasis on inductance was to remain ignored until Pupin in the United States decided to evolve practical means of adding inductance to telephone cables. His solution was to add 'Pupin' coils at intervals to the lines, thus achieving artificial loading. The alternative of continuous loading by laying iron wire along the whole length of the copper conductor was introduced by a Danish engineer, named Krarup, and short lengths of this type were made by the Germans for Denmark in 1902. The first British-made cables of either type were not to appear until 1910, and this loss of initiative was due almost entirely to the lack of technical appreciation and leadership of the Post Office. I have already referred to the very honourable amends made in this field by succeeding generations of Post Office engineers, culminating in the recent transatlantic achievement. The first cables used for telephony were insulated with gutta percha as they were merely adaptations of telegraph cables. In the search for lower leakance, an alternative material, balata, was introduced from South America, and after a great deal of development work on processing, it held the field for submarine purposes until the comparatively recent introduction of polythene. Meanwhile, telephone connections between towns and cities were established mainly by overhead lines, while multi-circuit cables soon became necessary in the towns. For this purpose, lead-covered cables were introduced, at first filled with insulating material, such as paraffin wax, but soon to be greatly improved by the adoption of the dry-core technique, where the individual wires are covered with dry paper and advantage is taken of the air interstices to obtain low capacitance.

By the beginning of this century, covered conductors and cables were being required in considerable variety for many purposes, and this process has extended over the last fifty-odd years to such an extent that the manufacturers now devote whole factories to different specialized products, and each of these is concerned with hundreds, or even thousands, of different types and sizes. I cannot possibly encompass the whole range in one short address, and will therefore content myself with mention of one or two of the more important high-lights before turning to the second part, in which I propose to deal with some of our present-day problems and developments.

On the power cable side, the increase in power generated and

transmitted has led to continual increase in both voltage and current requirements for cables. As voltages increased it soon became apparent that special means would be required to prevent or suppress ionization within the cable dielectric if any length of service was to be achieved. At first progress was made in improved impregnation methods and materials and in stress control, particularly by screening, but these alone were not sufficient to remove the inherent electrical weakness arising from the effect of heating cycles. As is now well known, these defects arose from the expansion and movement of the cable compound, causing eventual distension of the sheath beyond the elastic limit and the formation of voids in the dielectric in the region of highest stress. The first effective solution of these problems was invented by Emanueli in 1920. He employed a thin mineral oil under pressure from reservoirs at predetermined points in the system. The cable was so designed that free movement of the oil along the cable ensured complete elimination of ionizable voids under all conditions of operation. Although great improvements have been effected by Emanueli himself, and by his Italian and British friends and colleagues, the oil-filled cable remains in principle as originally designed by him. Cables of this type are manufactured in this country by three or four of the leading cable companies, and the majority of the highest-voltage installations, both here and abroad, employ this system. We are particularly glad that Dr. Emanueli is a member of this Institution.

The alternative of using high-pressure gas to suppress ionization was first conceived by Fisher and Atkinson in 1920 and patented in the United States in 1925. Many years were to elapse before there was any exploitation of these ideas in America. In Great Britain, however, four of the major cable companies evolved solutions of the many practical problems. Although development was seriously interrupted by the Second World War, there are now a large number of important installations employing these types of super-tension cables.

One other main preoccupation of the cable maker during this period deserves particular mention, and that is the development of cables for wiring houses, public buildings and industrial premises. The earliest installations were wired with conductors insulated with paraffined cotton, but this material was soon to be replaced by rubber mixtures of varying degree of efficiency.

By June, 1882, there was sufficient concern about the risk of fire to justify the preparation, by the Society of Telegraph Engineers and of Electricians, of their first 'Rules and Regulations for the Prevention of Fire Risks from Electric Lighting'. These were very short and dealt mainly with the necessity of eliminating moisture and making good conductor joints. Cables are dismissed in one sentence, 'All wires used for indoor purposes should be efficiently insulated', and by a reference to the desirability of affording protection against abrasion and 'the depredations of rats and mice'. There was also a footnote urging frequent testing, as 'escape of electricity cannot be detected by sense of smell as can gas'. Incidentally, an external switch was advocated, so that the supply could be cut off at once in the event of the potential difference between any two points in the house exceeding 200 volts.

By 1897, a new set of 'Fire Rules' was published. This had been prepared by a technical committee comprising the whole Council together with other experts. It was now concerned, not only with lighting, but with the supply of electrical energy. Various systems of wiring were being advocated, and from these two emerged which were to survive the test of time; these were the steel conduit and the lead-sheathed systems. Great improvements in the production of appropriate rubber compounds were effected, together with improved methods of applying the insulant and sheath, and the subsequent vulcanization process.

As the years passed, electricity spread as a source of power in many industries, including mining, where very special precautions were required, resulting in the development of special types of cables. The introduction of electricity into ships, both civil and naval, produced a new batch of problems. Later additions to the list include aircraft and rocket missiles, and doubtless we may anticipate new demands upon us as a result of man's desire to travel in space.

Another group of cables has been required for signalling purposes, first, of course, for the railways. The First World War created a considerably enhanced demand for cables of this type, but no other very notable changes in technical requirements arose during the period 1914–1918. The normal products of the industry, however, continued to be in great demand throughout the period of the war. So much so, that in 1918 an official committee reported as follows:

> The manufacturing of electrical machinery and apparatus in Great Britain has been with few exceptions far from prosperous . . . The notable exception has been cable making, which has been consistently successful in maintaining its lead, both in the quality of its manufactures and in financial results, and has been able to hold its own in the world's markets.

Between the two wars, although considerable technical progress was made, there was no very radical change in the materials employed. Manufacturing techniques and processes were improved. National and international standardization proceeded apace. Specifications were tightened. Considerable economy in the use of materials was effected. Business was conducted at a profit level which enabled the leading manufacturers at least to keep pace with plant and process improvements. Despite keen competition, and the gradual increase in the number of companies engaged in cable work, trade expanded steadily both at home and abroad, except, of course, during the general trade slump in the early 'thirties. It was in the field of super-tension power cables that the most notable technical advances were achieved, and I have already made reference to some of these. A number of important Institution papers were read and discussed by cable engineers and by cable-user engineers, and good attendances, with the debate ranging from friendly criticism to downright denial, could be guaranteed.

During the whole of the process of expansion in cable business, both in quantity and type, parallel needs had developed for the many fittings, accessories, pillar units, fuse units, joint boxes, sealing ends, etc., that were required. This has now become a highly technical and specialized trade in itself. Although there are now a few companies concerned with some aspects of this business who are not cable makers, the largest cable making concerns have built up very considerable departments or factories for these purposes.

The Second World War had far greater effect on the work of the cable engineers than the first had done. The first impact was a sudden demand for high-frequency cables, for radio and radar. As the war progressed, higher and higher frequencies were employed and the requirements became very stringent. Great accuracy and consistency in manufacture became essential, and the new plastic material, polythene, came into the picture.

The difficulty of obtaining adequate supplies of raw rubber necessitated a rapid examination of the possibilities of synthetic materials, including the now well-known polyvinyl chloride, or p.v.c.

In addition, the larger companies were called upon to develop cables for special purposes, including the so-called 'buoyant' cable for dealing with mines at sea, and, of course, the famous H.A.I.S. 'cable', which consisted of a strongly reinforced continuous lead tube laid across the Channel to supply petrol to the advancing allied armies. I do not propose to elaborate on

these and other war-time cable achievements, as these have been well recorded and documented in the Institution *Proceedings* and elsewhere.

Up to the beginning of the war, certain basic materials and processes had become so well established that it had begun to look as though they would never be seriously challenged. Since the end of the war, however, the position has changed very drastically, and I propose to draw your attention to some of the more important of these changes, which have had a profound effect upon the general economy of cable making.

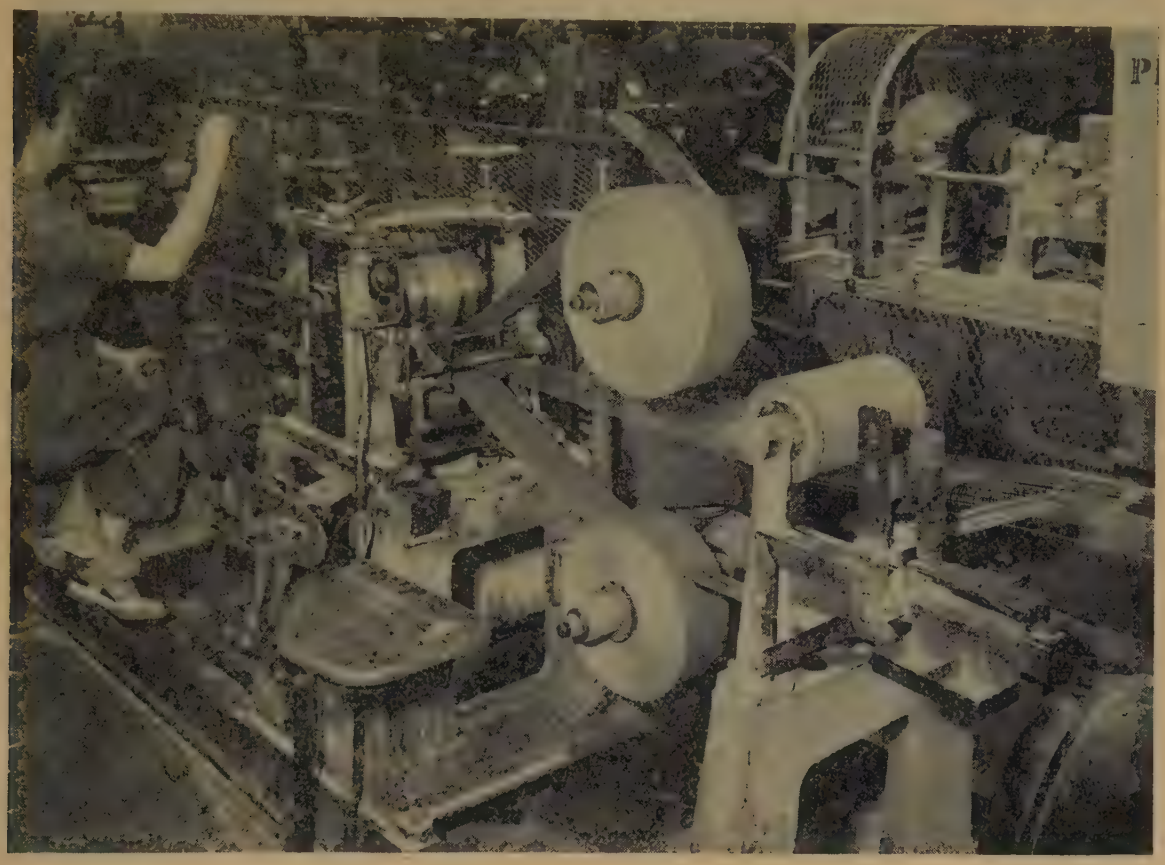


Fig. 1.—Covering of conductors by the longitudinal method.

The primary factors which have brought about these changes are:

(i) Introduction of new plastics.
(ii) Need for greater economy in the use of materials.
(iii) Introduction of synthetic rubbers.
(iv) Advent of entirely new processes due to rapid growth in the cable-plant manufacturing industry.
(v) Development of automatic control systems.
(vi) Competition in world markets from Continental manufacturers.
(vii) Increasing demand for cables for special purposes and arduous conditions, such as high temperature, low temperature, operation after fire, etc.

The first example which I have selected is concerned with the manufacture of the smaller sizes of rubber-insulated and -sheathed cables, such as those with which we are all familiar in domestic applications.

The well-established method of covering, usually called 'longitudinal', includes the following processes. After preparation of the appropriate rubber compound in the form of slabs, a calendering process, similar to that used in paper making, is employed to produce thin uniform sheet. This sheet rubber is cut into long strips which are rolled up and mounted, so that they can be fed in pairs between grooved rollers. The wires to be covered are passed through the rollers in the grooves and between the two strips of rubber. By appropriate design of the grooves and adjustment of the gap between the rollers, it is possible to cover the wires with seamed rubber. As many as 36 wires can be passed through the same number of grooves in one pair of rollers. This process can be repeated in tandem by using two more pairs of rollers in the same machine, thus producing the well-known 3-layer dielectric. Fig. 1 shows one of these machines in operation. The covered wires are taken up on reels at the far end of the machine. Subsequently, these covered wires, or cores, are rewound on to drums which are wheeled into a large vessel into which low-pressure steam can be fed to effect vulcanization of the rubber.

A further rewinding process is necessary after vulcanization before the finished core is ready for the further operations necessary to produce a finished cable. It will be appreciated that this method is far from efficient, involving as it does several discontinuous processes, particularly at the longitudinal-covering machine itself, which has to be stopped each time one of the coils of strip rubber runs out.

The modern alternative, developed since the war, is known as 'continuous vulcanization'. In essence it may be described as follows. Rubber compound in the form of thick strips is fed into the hopper of a rotary-screw extrusion machine, so designed that the compound is forced on to the wire to be covered as it passes through the 'head' of the machine, at a fairly high speed. Immediately on leaving the head the covered

wire passes into a long well-lagged steel tube containing high-pressure steam. Lengths of the order of 150 ft are usually employed. At the far end of the tube, the now vulcanized core is passed through a high-pressure water bath and wound up on to large spools. In its most highly developed form, as illustrated in Fig. 2, this plant is run continuously for a whole working shift of eight hours, or even longer. Arrangements are provided for feeding in the bare wire from a succession of drums without any interruption of the extrusion process. Similarly, at the far end, take-up on to a succession of drums is provided without any necessity for stopping the machine. Moreover, fully automatic control is provided, so that any variation in the thickness of the rubber covering is immediately corrected by an automatic adjustment of speed, effected by electronic control equipment. The finished core is produced to very close tolerances. Incidentally, this equipment is usually designed and developed by the cable maker. Some of the leading cable makers now have several complete units of the kind I have described, not only for the production of the core but also for a range of small- and medium-size sheathings. For larger-diameter sheathing, extrusion of the rubber compound is employed, but the vulcanization is discontinuous.

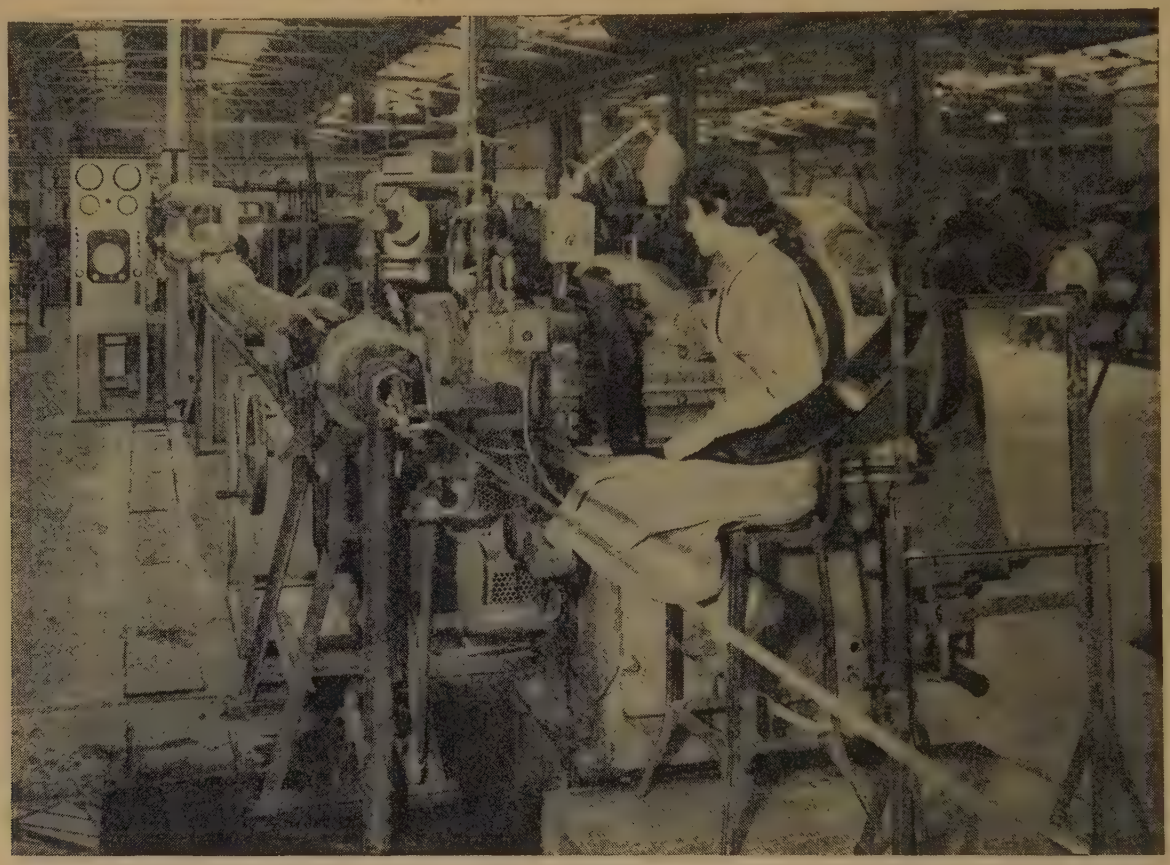


Fig. 2.—Continuous vulcanization plant.

Unfortunately, it is not possible to produce the whole output of small- and medium-size rubber core and sheathing by this method. The reason is purely one of economics. Due to the large variety of size, colour and type of rubber core and cable required, it is not always possible to ensure a sufficiently long run on one continuous-vulcanization unit to justify set-up. The manufacturer's occasional reluctance to accept a change of colour coding for a particular application will, I trust, now be appreciated.

Naturally, a transition of this magnitude has not been achieved without overcoming a multiplicity of new technical problems, many of which have only been solved by introducing high-precision engineering methods. Very considerable chemical problems also required solution, for the compounds evolved for the older process were not found to be entirely satisfactory for the new one. Very close collaboration between engineers and chemists was necessary to perfect the processing and ensure high-quality production. Some consequent changes in the appropriate British Standards have been made comparatively recently.

Of the several plastic materials produced in the last twenty or so years, polyvinyl chloride has so far proved to be the most important for general cable-making purposes. Direct extrusion methods are employed for both core and sheath of a wide variety of cables, many of which were formerly produced solely by using rubber. At first, attempts were made to extrude p.v.c. by using plant designed for the extrusion of rubber compounds, and although some progress was made, it was soon realized that specially designed plant would be required for efficient production. Considerable progress had been made by one or two plant manufacturers in the United States; consequently, during the war, plant was imported from America for this purpose and allocated to several British cable makers. Since that time, however, improved plant has been evolved in this country, and in some respects at least it offers advantages by comparison with American practice.

The preparation of p.v.c. compounds for the different purposes required by users is a highly complex and specialized study in itself. Some p.v.c. compounds are now obtainable from the chemical industry in a form suitable for the extrusion process.

Those cable makers who use large quantities and/or supply special-purpose cables, find it desirable, or necessary, to purchase the polymer, plasticizers, stabilizers and other ingredients, and evolve their own compound formulae. In addition to the elaborate mixing plant required, further equipment is necessary in order to produce the compounded p.v.c. in suitable pellet, or granule, form for feeding into the hoppers of the extrusion machine. Mixing plant as used for rubber compounds has also been employed successfully for p.v.c. compounds. Fig. 3, however, shows one of the most modern plants recently installed specifically for the preparation of p.v.c. compounds. Not only does this installation produce the compounded p.v.c. in suitable form by a continuous process, but specially designed arrangements are incorporated so that the proportions of various components can be altered by pre-setting, and thereafter these proportions are maintained automatically.

While on this subject, it may be as well to mention another growing use of p.v.c. which has recently required further capital investment, namely anti-corrosion servings. In order to protect the lead or aluminium sheath of a cable, either from the corrosive effects of soil waters or from the acids produced when textile servings rot through bacterial attack, it is necessary to provide protective layers over the sheath and/or, where the cable is particularly important or conditions are very bad, protection over the armoured tapes or wires. It is often sufficient to provide lead-sheathed cables with bitumen compound held in position by layers of paper and cotton tape, or p.v.c. tape, but for aluminium sheaths and for the better protection of lead sheaths, a more impervious layer is to be preferred. Rubber has been used extensively for this purpose, but more recently extruded p.v.c. sheaths have been successfully employed. This has necessitated the development of large p.v.c. extrusion machines which are installed in the paper cable factory.

The other plastic material which is of major significance in the industry is polythene. I have already mentioned the introduction of this material for high-frequency purposes. It is very suitable as a dielectric for low-voltage use owing to its excellent electrical properties. For such purposes as house wiring, fairly large quantities of cable have been used in this country, the polythene core being protected by p.v.c. sheath. Fortunately for the cable makers, relatively minor modifications to p.v.c. extrusion plant are required for the production of small polythene core. The fact remains, however, that they are now producing at least three varieties of these cables employing different materials for the same conditions of service. There are one or two important differences in the behaviour of the three materials which should be borne in mind when the problem of choice arises. Of these, I would mention the following.

Ordinary grades of polythene melt at temperatures slightly over 105° C, so that cables using this material are more prone to damage by sustained overload or short-circuit. It is true that some of the high-density grades now becoming available have slightly higher softening temperatures. Moreover, considerable improvement can be obtained by irradiating with neutrons in an atomic pile, or with electrons from a linear accelerator or high-energy Van de Graaff generator. Such treatment effects cross-linkages between the molecular chains and so eliminates the sharp melting-point. Instead, the material becomes rubber-like at temperatures of the order of 150° C. Unfortunately, the process is expensive, and it appears unlikely that polythene treated in this way will be used for anything more than special applications. Polyvinyl chloride, on the other hand, becomes softer as the temperature increases, and while it has no sharp melting-point, is subject to the disadvantage that serious deformation under mechanical stress could occur at the higher temperatures. Neither material is able to withstand the overload conditions that can be tolerated by vulcanized rubber, without serious consequences.

Polythene has also been employed successfully for higher voltages up to 11 kV, although its use has been very restricted in this country up to the present.

In addition to plastic materials, a number of synthetic-rubber materials are now available. The monomers which form the base of these materials are usually obtained from the petroleum base by the cracking process, in which the complex hydrocarbons are broken down into simpler ones by being passed over catalysts at appropriate temperatures. Developments in this field have been more rapid in America than here, and although there was considerable need for synthetics during the war, interest has waned since, except for special applications and for export purposes. The styrene-butadiene type, usually referred to as GR/S, has no particular advantages over the natural product and is now very little used in this country.

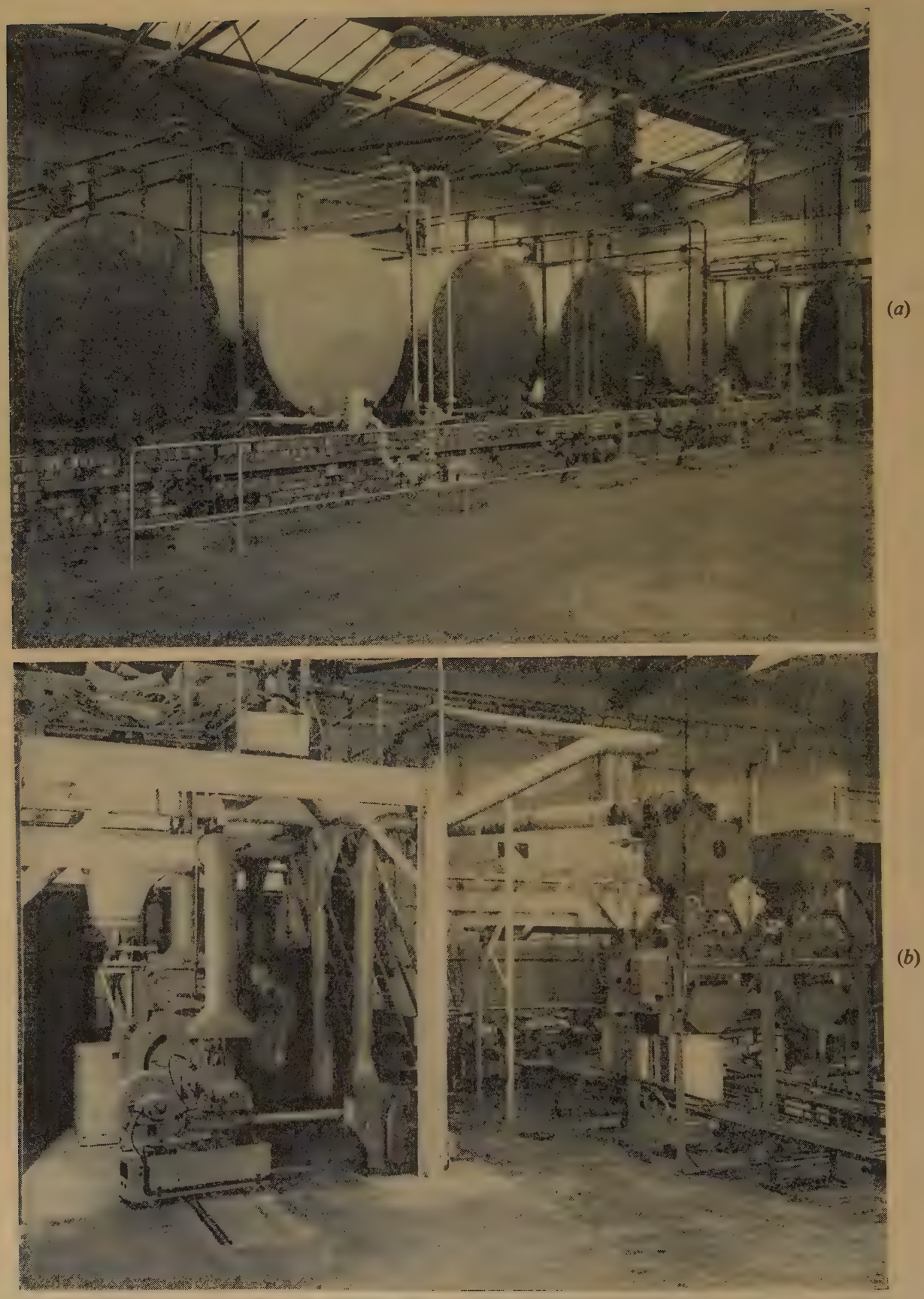
Polychloroprene, or Neoprene, which contains about 35% of chemically combined chlorine, is used for applications where good resistance to oil and water is required. It also has the advantage that flame does not spread along the material. It is, however, inferior electrically and is therefore usually employed for sheathings and not for dielectric purposes. Fortunately, plant and process problems are relatively minor.

Butyl rubber, which is a copolymer of iso-butylene and isoprene, is receiving increasing attention, particularly as it is specified for certain high-voltage export purposes. This material is resistant to oxidation and is of low chemical reactivity. Processing is, however, by no means simple.

Another particularly important synthetic is silicone rubber. This may be regarded as half organic and half inorganic, as the backbone of the molecular chain is a silicone-oxygen linkage, similar to quartz. It offers certain unique advantages, and for this reason is now being used in H.M. ships and in aircraft. It has exceptional resistance to heat, and will operate indefinitely at 150° C, and at considerably higher temperatures for short periods. After a fire, cables will continue to function if not disturbed, as the residue is largely pure silica. Flexibility is retained down to −70° C. The electrical properties are similar to those of natural rubber. Again special processing is required. Fairly large quantities of cables employing silicone rubber are now being produced.

From the foregoing examples, it will be evident that there has been a considerable strain on the cable makers' capital resources since the war, and that the demand by the industry for highly specialized scientists and technologists has also increased materially. Specifications for existing types of cables are under constant revision, and every endeavour is made to meet the users' demands for more economic construction for the same duties or for extension of permissible use for the same construction. None of these objectives can be achieved without a continuing programme of trial, experiment and research, and for effective results constant collaboration between the different interests concerned is absolutely essential.

In one respect the cable-making industry, and indeed the whole electrical industry, of this country has been fortunate. We have been assured so far of an ever-increasing home market on which to base a flourishing export business. Modern political trends, however, suggest that we may soon be facing Continental competition in our home market. It is true, of course, that should this happen Continental markets will also be open to us. Whether the redistribution of trade would be of benefit to British cable makers depends on many factors outside the scope of this address, but one important consideration, namely that of standards, is worth examination. Our own British Standards



(*a*)

(*b*)

Fig. 3.—P.V.C. compounding plant.
(*a*) Storage vessels for raw materials. (*b*) Compound-making plant.

for cables have been built up over the years on the basis of experience of successful service under our particular conditions of installation and use. They are established and modified by B.S.I. Committees, on which representation by users is predominant. Much of the experimental work upon which they are based is conducted by the principal members of the Cable Makers Association, who have established a structure of technical committees to provide this and other services for cable users. In addition, valuable basic information and data are provided by the staff of the Electrical Research Association, who have always been closely associated with cable problems, particularly those which have to do with rating. Our standards have formed the basis upon which many of the Commonwealth countries have developed and are developing standards to meet their own requirements. Periodic Commonwealth conferences are held at which mutual problems are discussed, and whenever possible common policy is adopted. On the Continent, there are one or two sets of standards which are different from our own in many respects. At the present time a great deal of attention is being devoted to the possibility of reconciling these differences in whole or in part. There are, of course, differing opinions in our industry and among the users concerning the desirability of adopting Continental standards in this country. For, let's face it, that is really what reconciliation of differences will very largely amount to, since we speak as only one voice in many of the international conferences, such as I.E.C. and C.E.E., where such matters are discussed. My own view is that the British cable user would be most unwise to agree to such drastic changes without very careful consideration of all the detailed factors involved. The whole subject of standards and standardization is very complex. Over-standardization and premature standardization should always be avoided, as they retard technical progress and discourage research and development. On the other hand, our own British Standards provide the best possible safeguard and assurance of high quality, good performance and long life.

And now what of the outlook for cable making in Great Britain? First, let us look at some of the technical possibilities and objectives.

Commencing with power cables for distribution purposes, the demand for the comparatively new non-draining paper cable has built up rapidly. This is the type in which the impregnant is a waxy material which is solid at operating temperatures. To-day an appreciable proportion of all low-voltage and high-voltage cables up to 11 kV are of the non-draining type, and there seems to be every indication that the demand will increase.

Meanwhile, considerable interest is being shown in the possibilities of plastic mains cables. P.V.C. has, of course, been used for some years for low and medium voltages for industrial installations. The Area Boards and the C.M.A. have been engaged recently in a joint study of the potentialities of p.v.c. mains cables, and a draft specification for further discussion has been submitted to the B.S.I. This covers p.v.c.-insulated wire-armoured cables for use up to 1 100 volts, and provides alternative beddings under, and servings over, the armour. One alternative in each case is extruded p.v.c. It would appear that some small economic advantage may be achieved by using these cables, but, of course, a cheaper form of construction could be employed if it were possible to dispense with the armouring and use a concentric neutral. The problem of live jointing for service conditions is by no means a simple one, however. A system employing these cables would involve the use of protective multiple earthing, and this would present considerable difficulties to the distribution engineer. It must be remembered that any plastic is likely to be inferior by comparison with paper under severe overload or short-circuit conditions. It is evident that it may be some time before these cables are used very extensively in this country, although I am confident that we shall see some installations of appreciable magnitude in the near future.

At higher voltages, up to 11 kV, polythene has been used successfully as a dielectric material despite the difficulty of ensuring an entirely void-free extrusion. For this reason, great care is essential during processing, and highly sensitive ionization-detection methods are used as a routine check of the homogeneity of the extruded material.

There has been discussion recently in national and international circles concerning the potential use of polythene for very high voltages. At present it appears unlikely that any extruded plastic material will be used for such purposes except for submarine cables, where polythene may well offer some advantages, particularly for direct-current transmission. It is noteworthy that views were expressed at the C.I.G.R.E. meeting this year that the limits for polythene were likely to be 33 kV a.c. and ± 200 kV d.c. For modern conditions of greater power and higher voltages, it is now evident that the highly developed oil-filled cable system can meet all the requirements which are likely to arise for many years to come. Within limits, this is also true of some designs of gas-filled cable. A good deal of money, time and energy has been devoted in recent years in attempts to produce super-tension cables capable of operating at high maximum working stresses. It is obviously undesirable to go too far in this direction, as the attendant operating risks are of necessity increased. Moreover, the apparent economy in price afforded by removing two or three layers of paper from the dielectric may be more than offset by other operating economics when the true value of increased running costs is taken into account. I believe the C.E.G.B. engineers are now, quite properly, taking these factors into account.

The drive for economy in use of materials in the manufacture of cables is now running parallel with the drive for economy in the use of the cables themselves. Although it would be relatively easy to determine the maximum current which should be carried by a cable under given conditions of installation, it is by no means so simple to state appropriate limits in practice, as most cables are subject to varying loads often in a daily cycle. They may also be subject to overload for long or short periods, particularly in times of emergency, and may have to carry occasionally short-circuit currents of considerable magnitude for periods dependent upon the rate of operation of the protective apparatus.

Until comparatively recently, most supply engineers have adopted a fairly conservative policy with regard to choice of cable size for a given duty, and there is little doubt that a proportion of the cable buried in the ground in this country has never reached the maximum operating temperature for which it was designed. On the other hand, it is well known, although seldom if ever officially admitted, that some distribution cables, particularly at the extremities of rapidly growing load areas, have been subjected to considerable overloads. In view of the necessity for national economy in such matters, however, some important investigations on cable utilization are now being conducted by the Electrical Research Association in conjunction with the Central Electricity Generating Board, the Area Boards and the cable makers. The primary objectives are to determine the effects of practical operating conditions with a view to better utilization of cables already installed, and to provide a more satisfactory basis for efficient specification of cables for new systems. At the same time, work is in hand to determine the limitations imposed by short-circuit considerations.

Future developments in cables for wiring purposes are unlikely to be revolutionary. The trend towards greater use of plastic

materials will undoubtedly continue. There will probably be continued effort in the direction of reducing dimensions, made possible largely by improved processing control methods.

As I have already indicated, a good deal of attention is being devoted to the development of cables capable of withstanding extremely arduous conditions. Much of this work has been concerned with cables for modern aircraft, where such considerations as lightness, toughness, ability to withstand extremes of temperature, or even to operate after fire, and to resist attack from modern fuels and lubricants are of importance. Some of the latest types of cables for such purposes are proving to be very successful in service, and there is little doubt that even the most difficult conditions imposed by aircraft designers will be met effectively.

Expansion of the use of silicone rubber for applications where higher-temperature operation is desirable, and/or where temporary operation after fire is required, will no doubt occur. For most purposes, it will be necessary to protect the insulation as the material is not resistant to all fuels and lubricants.

Improvements in p.v.c. compounds will extend the range of usefulness of this material, particularly for operation at slightly higher temperatures without material reduction in useful life.

All this, and much more, will undoubtedly be achieved by cable engineers, and we may be sure that we in this country will continue to play a leading part in many of the future developments.

There remains, however, for the cable-making industry as a whole, one fundamental problem which certainly must be tackled if we are to be able to face competition from abroad, both in home and export markets. It will be evident from the very limited range of examples that it has been possible to encompass in this address that the two bugbears of cable making are alternatives and variety. By this I mean alternative designs and materials for the same duties, and variety of size, type, colour, finish, etc., in the vast range of products. The former has particularly afflicted us since the last war and has led to constant demand for new plant and plant modifications far outstripping the gradual growth in gross demand for cables. The result has been that the industry as a whole now possesses surplus plant for many operations, although few, if any, of these operations are wholly obsolete.

If effective progress is to be maintained, two steps would appear to be necessary. First, the industry must be prepared to face the consequences of rationalization of production. This means effective regrouping of manufacture, and obviously requires close collaboration in one form or another between the different companies concerned. Technical collaboration has improved considerably in recent years, but this alone is not enough, important as it is to improve still further in this respect. Second, the cable users in their own and in the national interest must be prepared to accept some measure of restriction of choice. To this end, standardization must be directed towards the elimination of unnecessary complication and not aim at the inclusion of every twist, turn and vagary that can be thought up.

Finally, let us examine very briefly the possible scientific future to see whether there is any indication, even on the remote horizon, of the art and technology of cable making becoming redundant. As I see the position, there is no such indication. The atomic energy age, now so actively beginning, is making greater demands upon the whole electrical industry, including cable making. University laboratories are beginning to probe the possibilities of the thermo-electric generator as a source of power direct from heat. The fuel cell is also receiving attention as another possible source of small quantities of electric power direct from chemical reaction. The fact remains, however, that no convenient alternative to electricity capable of providing such a wide range of services is even remotely envisaged, and so far there is no indication that electricity can be guided and distributed, save in very minute quantities, by any convenient means other than the electric cable.

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MEASUREMENT AND CONTROL SECTION: CHAIRMAN'S ADDRESS

By J. K. WEBB, M.Sc.(Eng.), B.Sc.Tech., Member.

'THE SCOPE OF THE MEASUREMENT AND CONTROL SECTION'

(ABSTRACT *of Address delivered 14th October*, 1958.)

To be elected your Chairman is a distinction and I accept it with both pride and humility. I am deeply appreciative of this honour, which I feel is a very generous compliment, not only to me personally, but also to the great international telecommunication organization which I have been proud to serve during the past 34 years. During my term of office, I shall always strive to maintain the high standard of service set by my predecessors.

I propose to talk this evening about a number of subjects which come within the purview of our Section as it is now constituted, in order to illustrate its present scope, and I shall approach the task as one who has enjoyed a fairly long and varied career as an electrical engineer engaged in industrial research and development, besides several years' experience as a part-time lecturer.

The scope of the Measurement and Control Section has been greatly extended since its early days, and although it has never flagged in its concern for the more fundamental measuring devices, the impact of improved analytical methods, the continuous urge towards ever greater precision in the definition of our standards, the advent of new materials, nucleonics and improved measuring techniques, computers, data-processing and servo mechanisms, have all added to the complexity of its interests.

It is convenient to divide the work of the Section into five main 'panels', and I propose to give the heading of each in turn and then to indicate its scope by briefly discoursing on one or more relevant items.

Panel 1: Fundamentals, Standards and Laboratory Measurements

This panel includes notations and theorems besides the practical means of constructing and calibrating standards.

Let us first consider the question of notation, which is perhaps one of the most fundamental things in electrical engineering and concerns, amongst other things, our choice and representation of units. This subject may seem rather remote to many of you, but just reflect on what life would be like if we were obliged to do our sums in Roman numerals. Arabic notation, you must admit, has saved us much unnecessary thought. Now, as it happens, we have all suffered, perhaps without realizing it, from having been brought up on an ill-conceived notation, comprising a practical hotch-potch of modified unrationalized C.G.S. units with their unfortunate duality of electrostatic and electromagnetic forms stuck uncomfortably together, and with 4π's popping up in all sorts of odd places without any obvious relation to the geometry of the problem. It is a wonder that anyone is expected to think rationally in the framework of such a jerry-built and creaking edifice.

There is, happily enough, a very easy way out of this difficulty if we only have the courage to take it. That is, wholeheartedly to adopt the rationalized M.K.S. system of electrical units, not as just another system, but as one which we should use exclusively. This would result in a marked simplification of practical calculations and of the study of electrical theory in schools, besides saving much time and intellectual fatigue.

Conscious of its responsibilities in this matter, The Institution sponsored a symposium of papers on the M.K.S. system in 1950,[1] which provided an opportunity of presenting and discussing relevant technical matters. From this symposium it became abundantly clear that the universal adoption of the M.K.S. system would be eminently desirable.

Such also became the opinion of the Council, since in 1952[2] they adopted a resolution encouraging the use of the M.K.S. system, but still allowing authors freedom to use the C.G.S. system. I suggest that the time is now ripe for a stiffening of this resolution by making mandatory the use of the M.K.S. system in the *Proceedings*. This would, I believe, have two effects. First, by obliging members to take stock of the practical working of the M.K.S. system, it would remove many of the misconceptions which at present exist, and secondly, it would probably have a snowball effect on the attitude of other authorities.

Passing now to the consideration of electrical standards, we quite naturally associate this subject with the National Physical Laboratory. As an introduction, there are two excellent progress reviews published in the *Proceedings* in 1942[4] and 1952[5] by one of our Past Chairmen, Dr. L. Hartshorn, whose name is closely connected with that Laboratory. All electrical standards are ultimately referred to mass, length and time, and progress is still being made in defining these parameters. The precision with which mass can be defined has increased following recent developments in weighing techniques and is now about 1 part in 10^9, which is equivalent to 1 oz in 28 000 tons. Measurement of length which, for the past 75 years, has been made in terms of the platinum-iridium bar housed at Sèvres, will be made 100 times more accurate this year by the adoption of the wavelength of a particular orange line in the visible spectrum of an isotope of krypton, and will be definable to about $1 \cdot 5$ parts in 10^8, or 1 inch in 1 000 miles. Time and frequency, first measured in terms of the earth's rotation, then with crystal standards, and now in terms of molecular resonance, has yielded an increasing precision and now stands at about 3 parts in 10^{11}, or getting on for 1 second in 1 000 years. Such quests for greater precision are not purely academic, but are usually backed by very practical considerations, as, for example, problems in telecommunication and navigation.

Considerable ingenuity has been exercised in referring our electrical standards to the primary standards of mass, length and time. Thus the ampere is referred to mass by means of the Ayrton–Jones current balance, the ohm to length and time by Albert Campbell's bridge method and the henry to length by the Campbell standard of mutual inductance.

The determination of the farad has presented some anomalies in so far as it has always remained a secondary, derived unit, being measured in terms of mutual inductance and resistance by the Astbury–Ford modification of the Carey–Foster bridge.[6] This is rather a long way round, with inevitable loss of accuracy,

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and it is not surprising that experimenters have wistfully regarded the possibility of measuring the farad directly in terms of length.

A practical way of doing this has recently been suggested following the publication in the *Proceedings* of a very interesting theorem by Lampard,[7] for which he was awarded the Heaviside Premium. His theorem can best be grasped by considering a square cylinder constructed from four conducting plates which are insulated from each other at the corners as in Fig. 1.

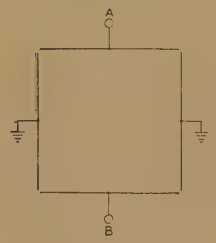


Fig. 1.—Square cylindrical capacitor which has constant direct capacitance per unit length independent of its size.

Lampard first showed that the direct capacitance between points A and B (neglecting corrections due to finite gaps) has a constant value per unit length independent of the size of the square. He then demonstrated that the same constant value was to be obtained from other configurations, limited only by the requirements that the cross-section have one axis of symmetry and that it be a closed curve. The capacitance of such a configuration is unfortunately rather small, being only about 1 pF per 20 inches, but it is completely defined in terms of a single measurement of length.

A configuration due to Thompson (mentioned in Lampard's paper), which has important advantages from the constructional viewpoint and which also minimizes the disturbing effect of the finite gaps, is shown in Fig. 2.

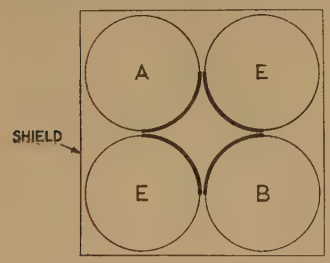


Fig. 2.—Thompson's capacitor standard, based on Lampard's theorem.

The four cylinders with which this capacitor is constructed can readily be machined with great precision. The direct capacitance between opposite cylinders such as A and B is, moreover, highly insensitive to the width of the gaps, tucked away, as they are, in re-entrant positions. End guards define the effective length of the rods.

This configuration, which takes the form of a 3-terminal capacitor, presents an interesting measurement problem, since the direct capacitance, which is only of the order of 1 pF, has to be determined with negligible error (say to about 1 part in 10^6 or to 1 μpF) in the presence of very much larger values of guard-ring capacitance. The outcome of this proposed system of measurement will be awaited with much interest.

Panel 2: Materials and Components

Leaving standards, we now pass to quite a different field of activity. Every year there appears some material which is particularly topical and which engenders a spate of technical literature as its characteristics and potentialities are explored. Such is now happening in the case of silicon, and only, be it noted, following the advancement of measurement techniques. Semiconductors have come more and more into the limelight since selenium was first used about 1927 in the manufacture of power rectifiers. It was not until 1948, however, that semiconductors really came into their own with the invention of the transistor. Germanium was then the favoured material, but despite its otherwise excellent characteristics, it has one disadvantage in so far as it cannot be operated at much above room temperature. Attention has therefore been focused on silicon, since it does not suffer from this limitation. Silicon exists plentifully in nature in the form of its very stable dioxide, silica. It is, however, a singularly difficult element to isolate in the very high degree of purity required for making transistors. Although a grade 99·95% pure had been produced during the Second World War and was used for making crystal mixers, such silicon is still far too impure for making transistors. Many workers therefore concentrated on the production of a more suitable 'hyper-pure' silicon, and about 1948 such a grade became available. A typical example was that made by the so-called du Pont process, which involves the vapour phase reduction of silicon tetrachloride with zinc at about 950° C in a fused-quartz apparatus.

The evaluation of the quality of such silicon is a big subject by itself, since the most sensitive chemical and physical tests, including mass spectrometry and activation analysis, are of little avail. We therefore become almost entirely dependent on electrical measurements made on monocrystals, but it is nevertheless astonishing how, from measurements which are basically simple, but which yet require great skill and care in their performance, it is possible not only to determine impurity levels down to such fantastically low values as 1 part in 10^{12} (which is equivalent to a single grain in 1 000 cubic yards of sand), but to designate the various elements contributing to this impurity. The measurements in question are simply those of resistivity and Hall effect at various temperatures.[9]

The relationship between resistivity and impurity concentration at room temperature, deduced from physical theory and supplemented by measurements, is shown in Fig. 3.

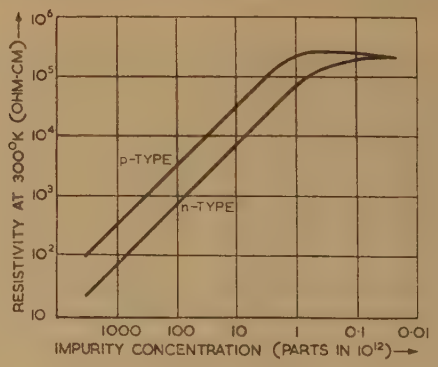


Fig. 3.—Curves which enable the impurity concentration in silicon to be determined from measurements of its resistivity.

The assumed mobilities are
μ_n = 1 700 cm²/volt-sec.
μ_p = 400 cm²/volt-sec.

From this it is seen that the resistivity of intrinsic silicon at room temperature is about 230 000 ohm-cm. It is not necessary to go to such extremes as this, however, even if it were possible, the practical aim being to produce a silicon of resistivity higher than 1 000 ohm-cm.

The more troublesome residual contaminant is boron, which cannot be removed by zone-refining methods; its effect is to produce a *p*-type material. Since there are invariably other

impurities present, the precise contribution of the boron by itself is usually unknown, and hence the material is of dubious quality. Moreover, to produce a satisfactory *n*-type material it is essential virtually to eliminate the boron. The trouble with silicon produced by the zinc reduction method is that, even after zone refining, there is still enough boron and other contaminants present to keep the resistivity down to about 100 ohm-cm.

To devise the means of producing a virtually boron-free silicon of resistivity greater than 1 000 ohm-cm has been a major undertaking and has involved considerable development effort. I am therefore happy to pay tribute to my colleagues, who by their genius and team spirit have succeeded in evolving a practical engineering solution to this most difficult problem.[8]

From the philosophy that it is generally easier to purify a gas than a solid, they first produced a gaseous silicon compound, silane, or silicon hydride, which, after extreme purification, was decomposed to form silicon and hydrogen. It was then converted into monocrystal form by a process which did not involve risk of contamination from crucibles. Much ingenuity, including the use of such effects as magnetic levitation, has made this possible.

The device maker usually requires a comparatively low-resistivity silicon, which can only be effectively obtained by doping the original high-resistivity material with precise quantities of elements which are themselves of comparable purity. Thus, to produce good-quality *p*-type silicon, the additive may be diborane, and for *n*-type, phosphine, both of which are of the same order of purity as the original undoped silicon. The silane process, moreover, enables such additives to be uniformly dispersed, since they can be readily mixed in during the gaseous stage.

In conclusion, it is fair to say that we, in this country, have been first to produce, on a commercial scale, 1 000 ohm-cm silicon with a hole lifetime above 200 microsec for *p*-type material, and, now that it is available, many important developments in the transistor field should follow.

Panel 3: Measuring Techniques, Devices and Instruments

In this panel we have a wide and flexible choice of subject ranging from nucleonics to transistors. This must therefore be my excuse for deviating slightly from the beaten track and saying something about recent developments with which I have been involved and which have great practical significance. They concern means of securing good electrical connections, a subject of interest to those engaged in such diverse fields as power cables, domestic wiring, telecommunication, computers and electronic apparatus. In the present context, however, discussion will be limited to the connection of copper conductors of cross-section equivalent to that of a wire of approximately 0·020 in diameter, or No. 25 s.w.g.

From the very earliest days of the electrical industry, the soldered joint has been regarded as the best and most permanent means of connecting copper conductors together, and if well made by a skilled operator, it can still be recommended with confidence. Skilled operators, however, are nowadays at a premium, and so, with the number of permanent connections made annually reaching astronomical figures, we can no longer rely upon every soldered joint having been made with all the attention which it merits. For this reason the defective, dry soldered joint has become more and more of a menace, causing endless trouble and inconvenience in manufacture and service.

The advent of the printed circuit eliminated the necessity of making certain types of joint individually by hand, and hence also the human element. In this scheme, all joints can be soldered automatically by dipping them in a trough of molten solder. The initial deficiencies and vagaries which accompanied this process had the good effect of directing attention to the technique of soldering, which, in this case, lends itself to close control. Considerable improvements have consequently resulted which lend certainty to the operation.

Printed wiring, however, has a limited application and cannot readily be applied to such problems as making connections to relays in telephone exchanges. The deficiencies of the hand-made soldered connection therefore prompted the Bell Laboratories to investigate alternative types of connection, and in 1953 the first of a series of papers appeared under the general title of 'Solderless Wrapped Connections'.[10] There is, of course, nothing new in making a connection by twisting the wires together or in wrapping a wire around a terminal post. What *is* new is the exact way in which it is carried out, including the tool which makes the connection, together with the means employed to secure large contact area, high contact pressure, the storage of sufficient elastic energy to ensure at least 40 years' trouble-free service, and compactness.

The surprising thing is that such a wrapped connection not only equals but surpasses an equivalent soldered connection made by a skilled operator. Having once proved that, we can afford to dwell on its many other advantages, in particular its certainty, reliability, low cost, compactness and the ease with which it can be made with the ingenious specially designed wrapping tools now available.

This is a development which we were not slow to examine closely on this side of the Atlantic, and we have lost no time in absorbing the Bell Laboratories' technique and in carefully checking their findings. Naturally we have also sought improvements, and I would draw particular attention to one variation which we have developed and which may result in greater flexibility in certain instances than that originally envisaged. The Bell Laboratories have concentrated on what has been termed 'primary wrapping', or otherwise simply the *wrapped* connection; i.e. in connecting, say, a resistor to a terminal post, it is the actual resistor lead which is wrapped around the post. An alternative method, however, is to lay the resistor lead beside the terminal and bind both together with a separate piece of wire. This has been termed 'secondary wrapping', but is perhaps better described as the *bound* connection. Both types are illustrated in Fig. 4. It has been found that binding can give an

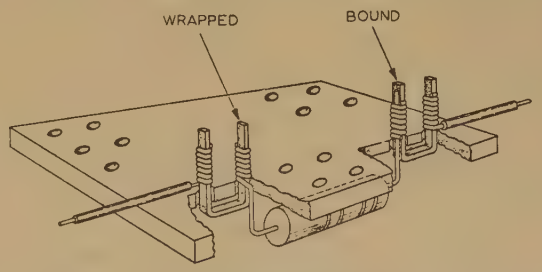


Fig. 4.—Sketch to illustrate the distinction between wrapped and bound connections.
Outer interconnecting wires are wrapped in both cases.

equally good connection and has certain advantages. The same size of binding wire may invariably be used and fed from a magazine power-driven wrapping tool. The optimum type of binding wire can be used. Such connections can be undone and remade repeatedly without damage to the component lead. Doubtless, however, both the wrapping and the binding methods will in time find their best spheres of application.

How to test a wrapped or bound connection to ensure that it would have a life expectancy of at least 40 years under all the adverse conditions it is likely to encounter has been a major

problem. As is well known, an accelerated test is not always convincing proof, but fortunately we have at least 10 years' field experience already available with less favourable types of solderless pressure connections, and this, together with the results of very severe accelerated ageing tests, has given sufficient confidence to warrant full-scale field trials. The ageing test includes resistance measurements before and after severe heat cycling, vibration, exposure to various humid and acid atmospheres, etc.

From the results of these tests, and from field experience, it has become evident that the wrapped or bound connection has much to commend it over the equivalent soldered connection and has effectively eliminated the dry-joint menace. Like all great inventions it has the supreme merit of simplicity, and is likely to play a very big part in future wiring problems.

Panel 4: Data Processing, including Analogue and Digital Computers

Referring in particular to the automatic digital computer operating at electronic speeds, this is a very recent innovation and one which is certain to have far-reaching repercussions as it comes more and more to insinuate itself into the conduct of our technological and business affairs. Already it has been successfully applied to scientific computations, to business accounting problems and to the control of machine tools.

The Section has a great responsibility in furthering the associated engineering problems, and this it has endeavoured to do by actively encouraging the presentation of technical papers which appear in the *Proceedings*. To cope better with the rapid rate of progress of the subject, however, the Section has also now instituted a new kind of forum taking the form of Specialist Discussion Meetings, which it is proposed to hold biannually, at which material, addressed essentially to specialists, can be presented and freely discussed with the minimum formality. The first of these meetings is planned for February, 1959, and details have already been published in the August issue of the *Journal*. It is envisaged that such discussions, together with the personal contacts which they promote, will stimulate ideas which can later be written up as formal papers.

Thus, by way of example, one session of the forthcoming meetings is to be devoted to low-temperature devices for storage and switching, and perhaps, without prejudice to what is to come, I may now say a few words about the very interesting topic of storage which is at present in such a rapid state of development.

A vital component of any digital computer is the memory, or store, into which intelligence can be inserted and from which it can subsequently be withdrawn. Up till about 1940, when the idea of applying electronics to computers was first mooted, the punched card served this function, but to cope with electronic speeds it became necessary to replace it with something much faster. Since then, practically every effect known to science which can be said to possess a 'memory', even including some unlikely ones such as thixotropy, and more esoteric ones such as spin echoes based on nuclear induction, have been and are still being diligently explored, and their relative advantages carefully weighed in relation to the problem in hand. Besides such general questions as reliability, ease of maintenance, the nature of the ancillary equipment, permanence, temperature dependence, volume, etc., the two most important questions to consider in assessing the merits of any memory system are access time (the time required to transfer information from the memory unit through the associated circuitry to the point of need), and economic factors including capital and operating costs.

Typical of those devices out of the many explored which have so far come out on top are magnetic tape, magnetic drums, magnetic elements and now, the latest, superconducting elements. The access time associated with these devices is indicated in Table 1.

Table 1

Typical component	Order of access time
	sec
Magnetic tape	10
Magnetic drum	10^{-2}
Magnetic elements	10^{-5}
Low temperature devices ..	10^{-8}

All such devices can store digits by virtue of the remanent magnetism which results from the application of a magnetizing force greater than a certain critical value. The relatively low cost of the magnetic drum, combined with large capacity and an access time which is short enough for many applications, explains its popularity.

One way of constructing a store of magnetic elements is to use tiny ferrite cores which must first be individually checked and then threaded with appropriate windings. The matrix, comprising a number of such cores assembled to form a co-ordinate array, is a typical example. At least two co-ordinate wires, an inhibit wire and usually a fourth 'reading' wire must be threaded through each core, and, with the desirability of making the cores as small as possible, this is not an operation which lends itself too easily to large-scale manufacture, taking a megabit store as a basis of reference (which is the size necessary to store the information of a small 30000-word novel). Alternative methods include forming the elements by means of ferrite wafers perforated with holes,[13] the ferrite in the immediate vicinity of each hole serving the same function as a discrete core, or else the use of deposited thin films of magnetic alloy. The capital cost of such stores is at present about 20 times that of magnetic drums of the same capacity, so that they tend to be limited to small buffer stores used in conjunction with the latter.

A recent and novel variant on storage in magnetic elements is the Bell Laboratories' Twistor,[11] which, by replacing ferrite cores with straight magnetic wires, would seem to facilitate large-scale production. The device depends upon a curious phenomenon, that, if a magnetic wire is twisted, magnetization will prefer to be along a helical rather than a longitudinal path. Its development will be awaited with interest.

There are other variants, including 'window'-type elements[12] designed to increase the switching speed, but these are more elaborate in so far as they have to be provided with supplementary windings to provide bias.

Anyone who undertakes such development work must always be distracted by the necessity of constantly looking over his shoulder to see how likely he is to be overtaken by some alternative scheme. For a time there was competition from cathode-ray tubes and ferroelectrics, but at present they do not appear to be in the running, although some fresh development may completely change the situation. The latest challenge, however, has come from a rather unexpected source—low-temperature devices.

The phenomenon of superconductivity in various metals at temperatures below about 10° K was discovered in 1911, but it never assumed engineering significance until helium liquefiers or 'cryostats' became commercially available in 1954, and an account appeared in 1956 of a superconductive computer component called the Cryotron.[14] This is a new circuit-element having power gain and current gain which can be used in flip-flop circuits, gates, counters and other computer circuits. In

1957 a memory cell based on flux trapped in superconductors by the application of a magnetic force above a certain critical value pointed the way to the design of a large memory having a cycle time of only 10^{-8} sec.[15,16] This very fast switching speed is of great interest to computer designers. Machines are now being designed to perform about a million arithmetical operations per second, and arithmetical circuits and stores act as each other's pace makers. It is too early even to hazard a guess at the capital and operating cost of such a store. Perhaps we shall learn more about it at the discussion next February.

Panel 5: Servo-Mechanisms and Control Systems

There has been much talk recently about automation, which, in the more popular sense, may be said to be an attitude of mind that is always seeking to decrease the labour content of any series of jobs. Although servo mechanisms are at the heart of automation, as engineers we are chiefly concerned with another more technical aspect, that of achieving by their means results which, by human agency alone, are very difficult, if not impossible. The whole subject has many ramifications some of which I can safely leave to our Vice-Chairman, Professor Tustin, whose recent contribution to the *Proceedings* will be published in November.[17]

For the present I shall simply endeavour to entertain you by directing your attention to some work carried out by D. A. Simmons[19] of the British Scientific Instrument Research Association and made available to me through the courtesy of one of our committee members, Dr. A. J. Maddock, whose excellent review of 'Servo-Operated Recording Instruments' was recently published in the *Proceedings*.[18]

The subject—that of magnetic levitation—is one which has fascinated me for some time, and whilst at present much of it is still a curiosity, I cannot help feeling that important practical applications may evolve, just as they have in the case of superconductivity.

Everyone must have observed the eagerness with which a keeper will leap up and engage with a permanent magnet once gravity has been overcome. With a piece of iron and a cored electromagnet, a similar thing happens as soon as the latter is sufficiently energized. To those unfamiliar with servo mechanisms it might seem incredible that they enable the force of gravity and the force of magnetic attraction to be so nicely balanced that the iron can be levitated and held quite stationary in mid-air, yet this is so.

As the iron approaches the core of the electromagnet it intercepts a beam of light which falls on a photocell. This controls the current in the coil of the electromagnet, and this current accordingly varies as the iron is displaced from a predetermined level. Whenever the iron tends to fall to earth, the current is increased and gravity is overcome, and vice versa. From this it is seen that there is a tendency for the iron to oscillate up and down, and here we come to a most important feature of any servo-mechanism system, that of damping out such oscillations. To do this it is necessary to arrange for the current in the coil to vary by an amount proportional not only to the displacement of the iron but also to the rate of change of this displacement. By adjusting the value of this so-called derivative control and compensating for any phase lag between effect and cause (in this case the current in the coil and the movement of the iron), virtually complete damping can be achieved.

It has been suggested that the scheme discussed could be applied to automatic weighing techniques, which may very well be so, but at all events I think you must agree it does very aptly illustrate the sort of thing which can now be done with the aid of servo mechanisms.

Conclusion and Acknowledgment

Many Institution members are perhaps a little hazy about the scope of the Specialized Sections. I have tried to enlighten them, at least as far as the Measurement and Control Section is concerned, by touching very lightly on just a few topics, picked almost at random, which have interested me personally, and which are published by kind permission of Standard Telecommunication Laboratories Limited. These may serve to indicate, however imperfectly, the wide range of subjects which now come within the Section's purview and, I trust, persuade members to participate more fully in its work.

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SUPPLY SECTION: CHAIRMAN'S ADDRESS

By D. P. SAYERS, B.Sc., Member.

'ART, CRAFT AND RAMPART'

(ABSTRACT *of Address delivered 29th October*, 1958.)

To-night I wish to take you for a quick tour over the territory covered by the Supply Section. As one who has spent all his career in the supply industry, I can only speak from personal experience of that side, but nevertheless I hope that our journey will touch on points of interest to all our members.

First, we should consider the territory to be covered. It would be true to say that the progenitor of the Supply Section was the Overhead Lines Association, which came into existence in 1927. In 1933 the Council of The Institution approved the setting up of a Transmission Section, which in effect absorbed the Association, for all its members who were members of The Institution automatically became members of the new Section. The first chairman was R. Borlase Matthews, and some of you may remember the other stalwarts of that time, such as Fennell, Eve, Hunter, Johnstone Wright and Kennedy, who have all passed on. Since the chair will be occupied to-night by the 25th Chairman, we may regard this occasion as a Silver Jubilee.

In 1948 the Council decided to broaden the scope of the Section and to rename it the Supply Section, the scope of which is now defined as including 'all matters relating to the generation, transmission and distribution of supplies of electrical energy'. The 'aspects' include design, manufacture, construction, maintenance and operation of all the plant and equipment employed, from the generator to the consumer's terminals.

Here may I emphasize the importance of the change which brought generation within the scope of the Section. We appreciate that this field is not the sole prerogative of the electrical engineer but must be shared with civil and mechanical engineers and fuel technologists. Nevertheless, generation is a basic branch of the electrical industry and our members have a predominant interest in it.

Broadly speaking, the Supply Section now embraces the major part of the heavy-current side of the electrical engineering industry, and that leads to the first point which I wish to make. To the schoolboy and the young engineering apprentice of to-day the heavy-current side has not the same lure and attraction as the lighter and newer sides of our industry, which have expanded at such a phenomenal rate during the past decade or two. It is significant that the number of papers submitted to the Supply Section last year was 38 compared with no less than 257 to the Radio Section. Another pointer in the same direction is that the number of graduate trainees recruited into the supply industry last year was less than a tenth of the number 7 years ago. The point I wish to emphasize is that there is still plenty of romance and even glamour left in heavy-current engineering and enough exciting problems to satisfy the best brains and the most adventurous spirits.

You may be wondering what the title of my address has to do with all this. All branches of engineering, and ours in particular, are becoming more and more specialized and in a sense more and more precise or scientific. Just as the hammer and chisel have given way to the power tool, so rule of thumb and simple arithmetic have had to give way to the computer, to operational research, statistical analysis, impulse testing and so on. These are the modern tools of the engineer, with a capacity and precision far beyond those available to early pioneers such as Ferranti and Lodge. But let us not forget that the accuracy of result rests on the judgment of the operator. Statistics are as sharp as chisels, and misapplied they can do just as much damage. With all the modern tools and techniques, the arts and crafts of the engineer are still needed to produce good engineering results. It might be said that engineering achievement is conceived in art, nurtured on science and justified by economics. That brings me to another point—which was indeed very ably developed by Mr. Ryle in his address here two years ago. An engineer not only has to make his project work but he has to make it pay. It is easy for the designer and planner to make things so large or so strong that they will never fail. It is much more difficult to make them just so large or just so strong that they will give the required performance at minimum cost. Half the art of engineering lies in perceiving the most economic performance and providing what is required—not just the best.

So much for the art and craft of our profession. What about the rampart? The object of our tour is to see the high spots, the towers and minarets thrusting their way up between the humdrum roof tops. To see the achievements and opportunities in perspective we must mount the ramparts and look beyond our own environment.

Our tour will not be confined to this country, because nearly one-quarter of the products of British electrical manufacturers are sent oversea, and it is very necessary for all members of The Institution to keep in touch with activities and developments abroad.

The Supply Section is fortunate in having one ultimate end-product to which all our members contribute in one way or another—namely the kilowatt-hour of electrical energy. The quantity, quality and cost of that unit to the consumer provide a direct measure of our efficiency. The records show consistent expansion with a doubling of the output every six or seven years—an eightfold increase between 1930 and 1955. Even the Second World War hardly affected the steady rate of progress. A unit of electricity to-day costs the consumer less than it did in 1920, notwithstanding that the real value of money has been halved over the years. Perhaps a better way of illustrating what the electrical industry has achieved is to point out that in the early 1920's, 10 lb of coal or 1 lb of bread would, roughly, buy one unit of electricity, but to-day 10 lb of coal buys 3 units and 1 lb of bread buys 4 units.

The average price of all units sold in England and Wales is almost exactly 1½d. It is interesting to note the main components of cost making up this figure. Generation costs amount to almost 1d., or two-thirds of the total, and include the largest single item of fuel. Distribution costs account for nearly the remaining third, with transmission responsible for the very small balance of just over 3%.

The point I wish to stress is that every member of the Supply

Mr. Sayers is with the Central Electricity Generating Board.

Section contributes directly or indirectly to these results, whether he be a designer of generators, a manufacturer of transformers, a power station operator or a mains engineer.

Generation

Thermal Stations.—In the field of generation we can see great advances already made in many directions and equally exciting developments round the corner.

In this country most of our electricity supply comes at present from steam stations burning conventional fuel. The war period naturally halted development of new designs, and the pressing need for additional capacity immediately after the war dictated a policy of using existing designs to provide 'quick kilowatts'. As the edge of this situation wore off, the natural tempo of advancement in design was restored and is now showing significant results. The trend towards larger generating sets and higher steam temperatures and pressures, and the use of improved techniques, all contribute to substantial economies in both capital investment and operating costs. Comparing a modern station containing 200 MW sets with a station containing 30 MW sets, which were commonplace before the war, the capital costs per kilowatt have been cut by a third and the thermal efficiency improved by a like amount. Fig. 1 shows that the overall cost per unit sent out from two such stations, with equal coal prices, has been reduced by some 25%, i.e. from, say, 0·88d. to 0·66d.

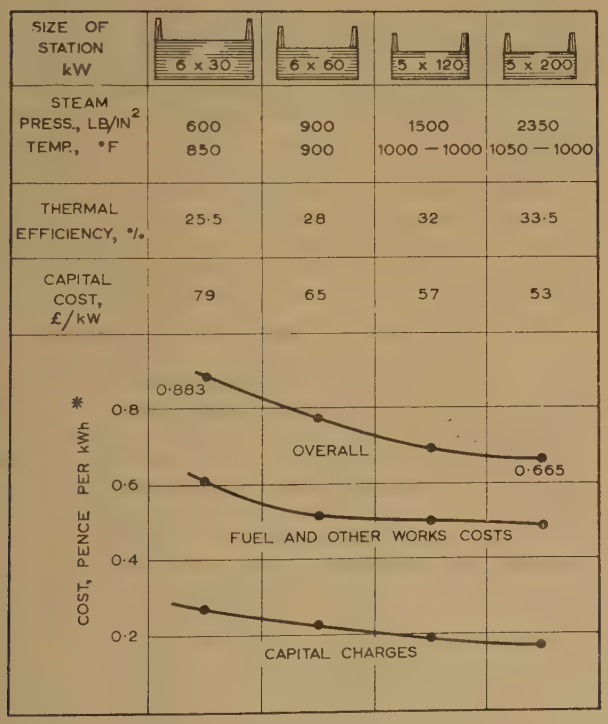


Fig. 1.—Trend of generation costs.

* At 60% load factor and delivered heat cost of 4d. per therm.

The increase in size and working conditions of generating plant has been made possible by improvements in materials and techniques to which the station designer, the metallurgist and the manufacturers have all contributed. The adoption of the unit principle of one turbo-generator and one boiler, with consequent simplification of layout and size of buildings, has effected substantial capital economies. The use of reheat in the thermal cycle allied to higher temperatures and pressures has been largely responsible for the improvement in thermal efficiency. Hydrogen cooling of alternators has reduced losses and made larger machines possible. The cooling of alternators has been one of the limitations to the use of larger machine size, and now this limitation is disappearing with the use of inner cooling—where an inert gas is circulated through hollow conductors. A further development, which has been pioneered in this country, is the use of water in place of gas as the cooling medium. The use of forced cooling of hollow conductors clearly offers prospects of economy wherever large currents have to be handled, as, for instance, in the external connections of very large alternators and in heavy transmission connections.

On the boiler side, there has been a corresponding increase in the unit size. Pulverized-fuel firing is rapidly superseding the chain-grate stoker because it is the only practical method of burning the small low-grade coal which is almost the only type now available for electricity generation.

The electrical end of generation has undergone radical changes, and it is now standard practice in this country to use alternators directly coupled to step-up transformers with switching at transmission voltages of 132 or 275 kV.

It is fair to say that British practice is rapidly catching up with the technological setbacks of the war period, and is now equal to and, indeed, in some respects, ahead of that of other countries. British manufacturers are at present building a 550 MW turbo-alternator with an optimum thermal efficiency of approximately 38%, its associated boiler having a capacity of no less than 1 670 tons of steam per hour. These are larger than any units building elsewhere.

So, by comparative standards, we may look upon present trends with some degree of satisfaction. But what about the absolute standards? Even in the most efficient station yet projected, about two-thirds of the heat input is wasted. Only 6 to 7 cwt out of every ton of coal delivered to the station appears as useful energy at the busbars. Is there not still a major challenge to the young engineer in this all-important field?

Hydro-Electric Stations.—Roughly 60% of the present-day world consumption of electrical energy is obtained from water power. The harnessing of the natural water of the earth in the service of man is indeed an inspiring example of engineering achievement. Some eight years ago I stood on the banks of the Swedish River Lule at Harsprånget just inside the Arctic Circle when the hydro-electric station was under construction, and I felt the ground trembling from the rush of water through the gorge. One could sense the latent power, but it served no purpose except to enhance the rugged beauty of that spot. Soon afterwards, the dam was closed and the water diverted through turbines which have since produced more than 12 million MWh of electricity for the people of Sweden.

Here in this island our water-power resources are very limited, with a little in Wales but most in Scotland. There are no great rivers, and it is only by heavy expenditure on dams, tunnels and pipelines that sufficient water can be collected to be converted to useful account. Nevertheless the hydro-electric output of the North of Scotland Board is now equivalent to nearly one million tons of coal per annum.

One of the largest hydro-electric schemes in the world at present in full commission is at Grand Coulee on the River Columbia in the United States which I was privileged to visit some years ago. It produces more than 2 000 MW of power, part of which is used to irrigate a million acres of desert and turn it into fertile land. The spillway over the man-made dam is more than twice the height of Niagara Falls and when in flood carries 20 times as much water.

Some very large installations are under construction in the U.S.S.R. On the River Yenusi in Siberia the Russians are said to be building a gigantic hydro-electric station capable of pro-

viding 5 000 MW with an annual output of 35 million MWh—a third of all the electricity used in Great Britain.

Of more direct interest to the members of this Institution is the Kariba development on the River Zambesi in Rhodesia. As you know from the paper presented last session, this work is well advanced with a planned initial capacity of 600 MW. You will remember the crucial struggle between man and nature last spring when the river rose higher than ever recorded before.

To me, the development of water power—the conversion of power which is literally running to waste into useful energy, often in the face of immense difficulties, but which does not, like coal or uranium, deplete the natural resources of the earth—is the very epitome of engineering achievement and something to fire the imagination of every engineer.

Nuclear Energy.—Lastly, in this section, I must include a reference to nuclear power generation. Here we have the outstanding achievement of the present age where the physicist, the chemist, the engineer and the metallurgist are succeeding in prising open an entirely new source of energy which may ultimately supplant all others. In the nuclear stations now building, four ounces of uranium fuel is expected to produce about as many kilowatt-hours as one ton of coal in a conventional station—an immense gain. Many important problems have yet to be solved, and even the disposal of the 'ash' from nuclear stations may be almost as big a task as that of the ash from conventional stations. It is indeed gratifying to reflect that in this sphere Britain leads the world, and no words of mine are needed to elaborate on the excitement, romance and sense of achievement which this new technology offers to the younger members of The Institution. As you know, The Institution has collaborated with our sister Institutions and other bodies in the formation of the British Nuclear Energy Conference as a common forum for co-ordinating activities in this new technology.

The economic necessity for operating nuclear stations at high load factor makes pumped-storage schemes economically attractive. One such scheme is now under construction in North Wales, where water will be pumped up 1 000 ft into a reservoir at night when there is power to spare. During the day this water will flow down through turbines to produce some 300 MW of useful power. It is interesting to note that the cost of storing alternating-current energy in this way is less than one-fifth of that of storing a similar quantity of direct current in accumulators.

Transmission

What steam temperatures and pressure are to the turbine engineer, so voltage is to the transmission engineer, and we see an almost continuous progression towards higher voltages, associated with growth in distance and/or capacity.

Overhead Lines.—The inherent economy obtained by the use of higher voltages is indicated in Fig. 2, from which it will be seen that the capital cost per kVA-mile of overhead transmission at 275 kV is one-sixteenth of the cost at 11 kV.

In this country the 275 kV Supergrid is now coming into effective use with some 1 000 miles of line completed and more than 7 000 MVA of transformers in commission. Our distances are comparatively short, and the main justification for higher voltage is the magnitude of the loads to be carried. The standard 275 kV double-circuit line has a gross thermal capacity of over 1 000 MVA—more than the output of any single existing generating station.

Transmission lines at 400 kV have been in operation for some time in Sweden, Russia, Germany and France, where the distances and loads make such a voltage economic. As to the prospect of still higher alternating voltages, the Russians are considering 800 kV for a 1 500-kilometre main trunk line, and in the United States it is assumed that 500 kV will be required in

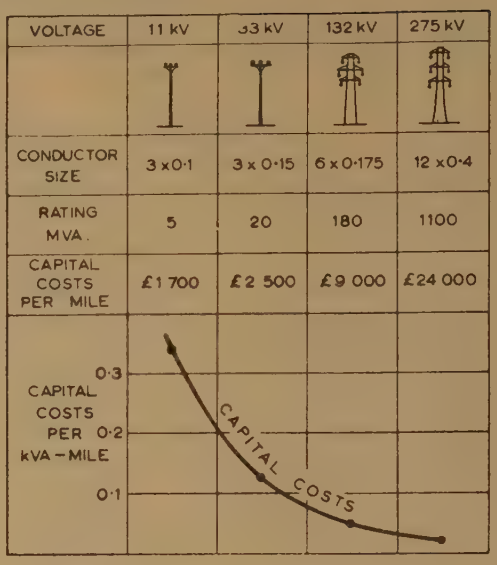


Fig. 2.—Trend of overhead line costs.

10 years' time. Work is about to start on a prototype line of this voltage. The insulation required for such higher voltages remains, however, a formidable problem, as, owing to non-uniform stress distribution, the conventional string of insulators becomes less and less efficient, particularly in industrial areas where the air is dirty. According to Dr. Forrest, if a 25-unit suspension insulator string is used without stress-control features on a 380 kV system, 40% of the voltage appears across the two units at the line end, whereas the last five discs at the earthed end account for only 6% of the voltage.

This problem remains intractable despite the considerable efforts made to overcome it, and the practicability of stepping up the British 275 kV lines to 400 kV without major reconstruction depends on its solution. Indeed, recent experience seems to indicate that the ability of very-high-voltage lines to withstand lightning is not up to expectations. If insulator characteristics could be improved, very great benefits would result in improved reliability and reduced costs of overhead line construction.

A notable piece of transmission engineering is the recently completed crossing over the Messina Strait. The main crossing span is 2¼ miles supported on towers which are twice the height of St. Paul's. The conductor sag in the crossing span is no less than 674 ft. The longest river crossing in the British Isles is at present under construction over the River Severn. In this case the main crossing span will be just over a mile long.

As regards developments in materials used for transmission, the use of high-tensile steel for towers has reduced the weight of material required, the British 275 kV towers showing a saving of 30% compared with mild steel. Equally important is the aesthetic improvement obtained by the use of thinner members.

Cables.—Contemporaneously with progress in overhead-line engineering, there have been significant advances in underground-cable technique. Short sections of 380 kV single-core cable are in service oversea, and in this country pilot lengths of 275 kV single-core cable have been in service under commercial conditions for the past 4 years. Three-core 132 kV cables are in use in the London area and elsewhere. The solid-type cable is used up to 33 kV, but above this voltage the cables are either gas-filled or oil-filled. At one time it looked as if gas would supplant oil, but oil has not been ousted and the battle continues.

The cost of underground transmission at 275 kV is about 15 times that of overhead construction of equivalent voltages and capacity, and is prohibitive for any general use of such

cable. What prospects are there of reducing cable costs? The use of high-voltage direct current as now being installed for the Channel connection between England and France may provide a partial answer, but it seems unlikely that such a system will prove economic for general transmission purposes except in very special circumstances.

A recent British achievement is the 138 kV submarine cable between British Columbia and Vancouver Island, which formed the subject of a paper last session. The single-core cables were manufactured in continuous 16-mile lengths and were laid successfully on the sea bed at a depth of 600 ft.

Transformers.—Transformer design and manufacture has advanced with the general growth in system voltage and capacity. The increased electrical and mechanical stresses of the modern system have been matched by developments in insulating materials and techniques, notable in the field of stress distribution and impulse testing. British transformer manufacturers have largely pioneered the on-load tap-changing equipment which is a standard feature of our Grid transformers, and is also generally used on our generator transformers. It is gratifying to note that practice in other countries is now following the same trend.

The main problem, in my view, is in the size of the individual unit, which is restricted by transport limitations. With the supply system doubling in capacity every 8–10 years, we must look for a corresponding increase in the size of individual plant items if we are to secure continuing economies of scale. At present, in this country, transport limitations restrict the unit size to between 200 and 300 MVA. I suggest there is scope here for developing new materials and techniques in fabrication and assembly to circumvent these limitations.

The use of cold-rolled steel permits the use of higher flux densities with significant savings in losses, weights and dimensions, and is making a valuable contribution to the problem. In many situations, however, where large transformers have to be installed in residential areas, the question of noise is important and any accentuation of it due to the use of higher flux densities may create serious problems.

Switchgear.—For service at the higher voltages, three types of circuit-breaker are available—bulk-oil, air-blast and small-oil-volume—and it is probably true to say that no one type has acquired decisive superiority. In this country there are now 100 breakers in service at 275 kV, mostly air-blast but some of the bulk-oil type. Service conditions are very onerous owing to the compact and tightly interconnected nature of our Grid system, which results in high fault energy levels and high rates of rise of recovery voltage.

Apart from keeping pace with growth in voltage and fault energy, the main problem, at least from the supply industry's point of view, is one of cost. It was stated at the Electrical Power Convention in 1957 that switchgear accounted for almost 30% of the total cost of Grid schemes approved. In my view this is too large in relation to other items. The achievement of economy does not rest solely with the manufacturers but calls for co-operative action between the system planners, the design specialists and the manufacturers.

System Operation.—With the additional interconnection capacity of the 275 kV Grid coming into commission, the scope for minimizing the overall costs of production on a national scale is considerably increased, and this is primarily the function of system operation. Of the many factors involved, some, like the choice and allocation of coal from the 1 000 collieries concerned, are, to some extent, controllable; others, like the load requirements and the amount of plant out of service due to breakdown, are uncontrollable and vary continuously. The most economic method of operating the system from minute to minute, taking all the many factors into account, presents a formidable yet fascinating problem involving a highly skilled technique.

Distribution

In the distribution field, the scope for greater economy and efficiency lies more within the realm of scientific management than with technology development. Nevertheless, in my view this field affords more scope for the art of engineering than perhaps any other. The engineer is dealing with so many unknown and uncontrollable factors: his problem is not so much to design for a specified load or performance, but to judge which performance should be selected as the basis for his designs.

The national daily maximum demands in summer and winter differ by some 60%, and there is an annual increase of the order of 6½% (Fig. 3). The distribution engineer has to visualize, not

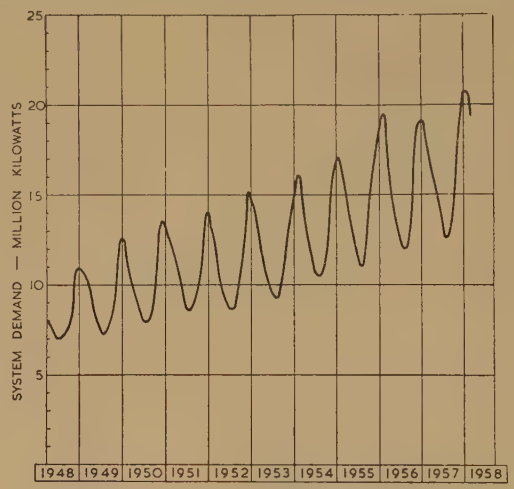


Fig. 3.—Growth of maximum demand.

only how much load has to be catered for, but where and when it is likely to develop and how far ahead he should plan when deciding on the equipment to be installed to meet immediate requirements.

There are nearly 15 million consumers in this country and they are increasing at the rate of 400 000 a year. The domestic consumers, totalling 13 million, are probably responsible for an average demand on the national peak demand of about ¾ kW per consumer. Nevertheless, in planning new distribution networks, it is necessary to allow for an after-diversity maximum demand per consumer of from 1½ kW to 3 kW according to the class of property. There is thus a very wide gap between the capacity provided and the actual average capacity utilized.

This leads to the point that the distribution engineer soon knows when his mains are overloaded—the fuses blow and the voltage falls—and if there are no voltmeters, the presence of some 8 million television sets connected to the mains tells much the same tale. But he has no such impelling indication when his mains are underloaded—when the money he has buried underground is not earning its keep. I would like to see schedules of underloaded mains and transformers given the same earnest attention at regular intervals as the schedules of overloaded equipment.

The intermittent or cyclic nature of many of the loads on the distribution mains throws into relief the importance of specifying and designing plant in corresponding terms. Considerable progress has been made in this direction in recent years, but there is scope for further study. The latest edition of B.S. 171 will take

into account the inherent short-time rating of transformers, particularly under emergency conditions. It is not suggested that a transformer should continuously work at its maximum rating—indeed this would be far from economic—but its ability to do so over the peak and under rare emergency conditions should be appreciated.

The intermittent and cyclic rating of cables is receiving close study by the Electrical Research Association in collaboration with users and manufacturers. Here again, I believe more accurate knowledge will enable the planning engineer to effect economies by fitting the cable size more closely to the actual working conditions, always bearing in mind that voltage regulation is frequently the limiting factor.

Cable costs form a very large item in distribution expenditure, and the time and skill required for jointing conventional paper-insulated lead-covered cable is a serious factor, particularly on house services. If the problems associated with plastic-insulated cables can be overcome, substantial economies should be possible in both materials and labour.

The very wide fluctuations in the price of copper, from the war-time controlled price of £62 10s. per ton up to a peak value of £440 per ton in 1956, has had a profound effect on network planning. In general, it has resulted in shorter and smaller low-voltage distributors with more extensive high-voltage distribution and a greater number of transformer points. It has also resulted in a substantial change from copper to aluminium conductors for both overhead lines and insulated cables.

In rural networks the installation of high-speed reclosers is an important development. In some parts of the Midlands Board Area, where these reclosers have been pioneered, over 90% of the faults which ordinarily cause sustained interruption to consumers are now known to be of a transient nature, and where the line is controlled by a recloser, these incidents do not cause interruptions to the consumer. The most striking developments in distribution transformers arise from the adoption of national standard specifications and the use of cold-rolled steel, the weight of rural transformers having been reduced by 26%, and their losses by more than 60%, since 1947.

The need for more economical and efficient use of labour in all distribution work is a problem which has received much attention by all the Area Boards. Survey work has been speeded up by the use of aerial surveys, and helicopters have been used on a limited scale on construction work. Mobile cranes and special transport vehicles facilitate the handling of heavy equipment. Mechanical excavators have been used for cable trenching. Radio-equipped vans are in fairly general use for fault work and other purposes. In the erection of rural overhead lines, more use is being made of pole-hole borers and other mechanical plant.

The use of plastic-insulated multicore cable supported on a catenary wire may be an economic alternative to the conventional overhead line where space is limited or amenities are involved.

Another small but important contribution to the problem of amenity is the joint use of power and telephone poles. It is no longer necessary to disfigure the village street with two sets of poles and conductors zigzagging from side to side.

Conclusion

Our tour is ended. In such a swift journey we have been able to catch no more than the most fleeting glimpses of the high-lights in generation, transmission and distribution at home and abroad. Nevertheless, I hope it will help some of our younger members to realize that the heavy-current side of our profession is not dormant, that the potentialities of development in the future are no less than the realizations of the past; that problems abound, the solving of which will bestow a real sense of achievement and endow a worthy career.

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UTILIZATION SECTION: CHAIRMAN'S ADDRESS

By R. A. MARRYAT, B.Sc.(Eng.), Member.

'INSTALLATION ENGINEERING'

(ABSTRACT *of Address delivered 16th October*, 1958.)

When the Utilization Section of The Institution was inaugurated in 1941, by our first Chairman, Mr. H. T. Young, attention was focused on the contribution of the installation engineer to the achievement of our industry. Since that time the Section has been broadened in scope to embrace more general aspects of the utilization of electricity, and it has been presided over by many distinguished engineers, drawn from all sides of the profession. As an electrical contractor I feel very greatly honoured to have been elected to this office and very conscious of the need to uphold the high standard that has been set by those who have preceded me as Chairmen of the Utilization Section. The design and execution of electrical installation work must still remain our particular concern in this Section, for it is our duty to ensure that the wiring in our homes, offices, factories and all other buildings is such as will facilitate full and abundant use of electricity, and that it will provide, not only for the present, but for future needs, of better living and higher productivity.

It has never been possible to lay down in The Institution's Wiring Regulations what should be regarded as an adequate installation in any particular type or size of building, and in fact it is emphasized in the introduction that the Regulations are not intended to take the place of a detailed specification. The preparation of such a specification, involving, as it must, the complete design of the required electrical installation, is often no simple task even for those who are fully conversant with the industry. Consultation with the architect, owner and occupier of the building and with those concerned with the provision of engineering services is necessary, but, even then, lack of complete and definite information in the initial stages of design is the rule rather than the exception, and it may be necessary to resort to experience in similar installations and to guidance contained in relevant Codes of Practice. Much thought is now being given to the revision and extension of the electrical Codes of Practice, and it is to be hoped that they may soon be recognized as authoritative guides to those concerned with the design of installations for diverse applications.

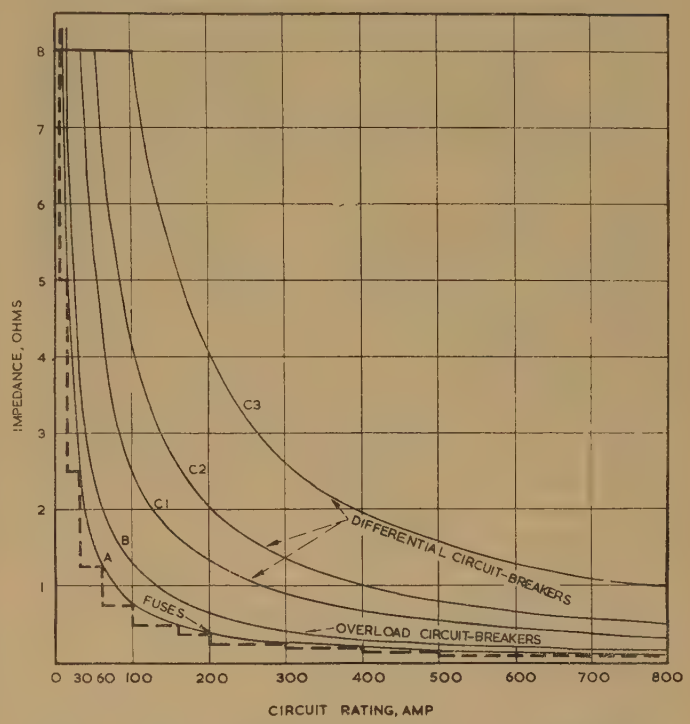


Fig. 1.—Limits of application of various forms of earth-fault protection.

A. Fuses, on basis: current = 3 × fuse rating.
B. Circuit-breakers, on basis: current = 1½ × circuit-breaker setting at 120% of full load.
C1. Differential-current circuit-breakers on basis: 40 volts rise with 15% out-of-balance setting.
C2. Differential-current circuit-breakers on basis: 40 volts rise with 10% out-of-balance setting.
C3. Differential-current circuit-breakers on basis: 40 volts rise with 5% out-of-balance setting.

Protection Requirements

Irrespective of the particular application of any installation, the designer must consider, at an early stage, the various alternative means of achieving circuit protection. This will entail examination of the distribution system as a whole, from the supply transformer onwards. In any installation supplied at low or medium voltage it will generally be necessary to make an advance estimate of earth-loop impedance at the intake position before design of the main switchboard and distribution boards can proceed. There is only a slender chance that the use of large fuses or circuit-breakers will conform with the requirement that, upon the occurrence of an earth fault of negligible impedance, a current corresponding to three times the rating of the fuse or one and a half times the setting of the overload circuit-breaker will flow, so that the faulty circuit is made dead. In Fig. 1 the maximum admissible values of earth-loop impedance are plotted against the full-load current rating of fuses or circuit-breakers that may be used. Curve B represents circuit-breakers set to trip at 120% of full-load rating; if, however, the settings were increased to 200% of full load the maximum admissible impedances would correspond to the lower curve A for fuses. I would suggest that it is unreasonable to assume, in planning any installation taking a load much in excess of 100 amp, that such results could be achieved, unless, at least, provision is made for an effective direct connection between the consumer's earthing lead and the star point of the medium-voltage winding of the supply transformer. Obviously, the lowest possible loop impedance will prevail when the supply transformer is installed in a substation within the consumer's premises, and bearing in mind the reduction in voltage regulation and freedom of restriction of connected loads thereby normally attained, it is clear that there is much in favour of installing the transformer within the premises wherever practicable. The further high-voltage distribution can be extended and the shorter the range of medium-

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voltage distribution, the more efficient must be the supply system and the lower the earth-loop impedances at consumers' premises generally.

Where an electricity supply has to be taken at medium or low voltage through an underground cable, provision should be made for an earth connection from the local supply transformer to a consumer's earthing terminal. Such practice was recognized in the 12th edition of the Wiring Regulations and is, I am glad to see, being increasingly adopted in a number of supply areas. In the past, much use has been made of water and even gas mains as consumer's earth electrodes, but we have no jurisdiction over the maintenance or repair of such systems, and undoubtedly an electricity supply service should be complete in itself, without need to resort to other systems for means of securing adequate protection. To be effective, it is my view that such connections from the supply transformer should be so installed and maintained that, upon the occurrence of a direct fault between the consumer's supply and earth terminals, a current corresponding to at least three times the rating of the consumer's service fuse should flow. At present the supply authorities accept no obligation in this respect, but it seems to me logical to divide the present indeterminate responsibility for earth-loop impedance in this way, at the consumer's terminals. Similarly, where electricity is supplied from an overhead line through a local pole-mounted transformer, an earthing conductor should be brought into the premises from a neutral point of the transformer; earth electrodes may then be used only as a second line of defence, where thought desirable. The alternative arrangement depending on protective multiple earthing must be used where this system is in operation, and it would seem that this may have interesting possibilities where permission can be obtained to use earthed concentric wiring in the form of mineral-insulated cables. In passing, it may be noted that, where the protective multiple earthing system is adopted, the supply authority does quite naturally accept full responsibility for the maintenance of an effective earthing terminal upon the consumer's premises.

Information regarding the impedance of the supply earth electrode is only rarely available to the installation planner, and conditions at the consumer's premises cannot easily be predetermined. Results of loop-impedance tests in several small factories around London have shown that the main fuse or circuit-breaker, of perhaps 200 amp rating, would not operate to isolate an earth fault, say, in the main busbar chamber, although the smaller fuses protecting the main circuits would operate satisfactorily. In such circumstances local supply transformers should be installed which would provide, as well, for future development; if that should be impracticable, some form of earth-leakage circuit-breaker would be necessary. A voltage-operated earth-leakage trip could be applied to the main switchboard only, provided that steps were taken to prevent unwanted operation due to faults on sub-circuits already adequately protected by fuses. This could be achieved by the isolation of the switchboard framework from incoming and outgoing circuits by insertion of insulating materials. If the need for such treatment were foreseen at the design stage of a new installation, I believe that it could be effected fairly easily.

In installations where the loop impedance is likely to be as high as one ohm it will be found that fuses are ineffective for earth-fault protection of distribution circuits rated at 100 amp, and furthermore, owing to the difficulty of segregating main circuit ducts or conduits, the use of voltage-operated trips becomes quite impracticable. Circuit-breakers fitted with differential current-operated earth-leakage trips and overload trips do afford discrimination between one circuit and another, and could in some circumstances be used for main circuit protection. Table 1 shows the actual leakage currents for various sizes of breaker based on operation at 15%, 10% and 5% out-of-balance current, and also the maximum values of 'consumer's earth impedance' that can be accepted if the voltage rise on exposed metalwork is to be limited to 40 volts when these values of leakage current flow. If such limitation of voltage rise can be accepted as a criterion of satisfactory protection, it will be seen that a 100 amp breaker of this type set to operate at 15% out-of-balance current could be applied where the consumer's earth impedance does not exceed 2·4 ohms, as compared with a maximum earth-loop impedance of 1·3 ohms for an overload circuit-breaker or of 0·8 ohm for a fuse of similar rating. Since the consumer's earth impedance does not include that part of the loop impedance attributable to the supply transformer, electrode and service lines, the limiting earth-loop impedance for the differential circuit-breaker would be greater, possibly in the region of 3 or 4 ohms. With 10% or 5% out-of-balance settings, even higher values of impedance would be acceptable, but a minimum operational leakage current of 5 amp is recognized in the Wiring Regulations, which, for 40 volts rise in potential, corresponds to a consumer's earth impedance of 8·0 ohms. In Fig. 1 the ordinates below the lines and curves indicate the effective limits of application of fuses, circuit-breakers set at 120% of full load and of differential-current-balance-operated breakers, in circuits of various current ratings. Here it has been assumed, in the case of the differential-current-operated breakers, that the whole earth-loop impedance is concentrated in the consumer's earth impedance, so that the actual field of application of these would be greater still in practice. At present 60 amp 3-phase circuit-breakers with differential-current earth-leakage and overload trips are available, but it would seem that there is room for development of larger breakers of this type, which should incorporate delayed action in the earth-leakage as well as in the overload trips, so as to afford discrimination with sub-circuit overload and earth-leakage protection.

Table 1

DIFFERENTIAL-CURRENT-BALANCE CIRCUIT-BREAKERS

Maximum Acceptable Values of Consumer's Earth Impedance if Voltage on Exposed Metalwork is limited to 40 Volts

Circuit-breaker rating	15% out of balance		10% out of balance		5% out of balance	
	Current	Impedance	Current	Impedance	Current	Impedance
amp	amp	ohms	amp	ohms	amp	ohms
500	75	0·53	50	0·8	25	1·6
400	60	0·66	40	1·0	20	2·0
300	45	0·89	30	1·3	15	2·4
200	30	1·3	20	2·0	10	4·0
100	15	2·4	10	4·0	5	8·0
60	9	4·4	6	6·6	5	8·0
30	5	8·0	5	8·0	5	8·0

In accordance with The Institution's Wiring Regulations, all differential-current-balance trips must operate at 15% out-of-balance current or at 5 amp out-of-balance current, whichever is the greater.

I venture to suggest that, if a survey were made of electrical installations in larger buildings completed before the issue of the 13th edition of the Wiring Regulations, it would be found that in many of them the basic requirements for earth-fault protection, now set out in Regulation 406, are not fulfilled. Substitution of a circuit-breaker of this type for the existing main switch, or the fitting of a suitable tripping relay to an existing circuit-breaker, would often overcome this difficulty and at the same time afford much better fire-risk protection. Some

reference was made to this in the paper read by Mr. H. W. Swann[1] as long ago as 1952, but little progress has yet been made in this direction.

In smaller buildings, such as local shops and private houses, insulating-sheath wiring systems or plastic conduits can be used to afford effective segregation of earth faults in separate sub-circuits, and in any case, continuity of supply is not quite so important as in larger buildings. It seems that there is need for development of a larger consumer's control unit than that covered by B.S. 1454, which was only intended for small houses. This might well incorporate a 100 or 150 amp main circuit-breaker and miniature circuit-breakers to protect 60, 30 or 15 amp sub-circuits as required. Normally, the sub-circuit-breakers would be fitted with overload trips only, but alternatively, where earthing conditions are difficult, breakers with additional voltage-operated earth-leakage trips could be used instead, at least for the larger sub-circuits. The main breaker would preferably be fitted with delayed-current-balance and overload trips, while the incoming service fuse would be of the h.b.c. cartridge type. Such a unit would meet a wide variety of needs, and would afford full protection against short-circuit faults, leakage from neutral conductors, and dangerous voltages on the metal framework of accessories or appliances.

The increasing use of h.b.c. cartridge fuses has done much to eliminate the danger arising from short-circuit currents in all classes of commercial and industrial installations. The problem of ensuring discrimination between the fuse protecting a main circuit and smaller fuses protecting sub-circuits of lower rating has been investigated, and it is recognized that this depends upon the total operating time of the minor fuse being less than the pre-arcing time of the major fuse; hence the margin required to secure discriminative operation increases with the prospective short-circuit current. Where cartridge fuses are employed as back-up protection in motor circuits, or where final sub-circuits in an installation are protected by miniature circuit-breakers, fuses of a type designed to discriminate with the normal operation of the motor starter or circuit-breaker, as described in the paper recently presented by Mr. R. H. Dean,[2] can be used to restrict operation of the fuse to short-circuits in excess of the breaking capacity of the protective equipment.

Distribution

In the interests of standardization there is a marked tendency to limit the size of medium-voltage distribution transformers to 500 kVA rating, even in closely built-up areas. This limits the lengths of earth-return paths, and places the maximum prospective short-circuit current at about 15 000 amp. In those buildings where heavy loads are concentrated in a small area, it may be convenient to install two or more such transformers in a single substation, normally supplying separate sections of the load. Transmission of large loads at medium voltage for even moderate distances without undue voltage drop can, however, be an expensive proposition, and subject to a satisfactory access, the substation should be sited as near as possible to the electrical centre of gravity of the load. Where considerable load is spread over a wide area it may well be economical to use high-voltage distribution to two or more strategically positioned transformer substations. Now that dry-type transformers are becoming more readily available, these can be installed with safety on the upper floors of tall buildings, so as to avoid the necessity for very heavy rising mains.

Bearing in mind the rapid development of new electrical applications that continues unceasingly, I would strongly urge that sufficient space should be allowed, preferably for a 100% extension, and invariably for a 50% extension, of every switchboard throughout any industrial or commercial installation. I doubt whether there is amongst us here tonight a single installation engineer who cannot immediately call to mind a switchroom that has been grossly overcrowded. By the introduction of cubicle-type boards considerable saving in space can be effected, but it is most desirable that no advantage should be taken of this to squeeze such boards into even smaller switchrooms. Insistence on ample space is definitely conducive to safer operating conditions, greater reliability in service and, in nine cases out of ten, long-term economy in cost of effecting alterations and additions to an installation.

From the point of view of economy it is interesting to study the cost of heating losses that occur in distribution cables. It was Lord Kelvin who stated that the greatest overall economy is achieved when the annual cost of heating losses in a conductor is equal to the annual cost of interest and depreciation upon the capital involved—but how many of us apply Kelvin's rule in the design of internal distribution systems nowadays? In fact, the relative economy of derating cables in order to reduce the cost of heating losses should be considered when designing any main distribution system. This is particularly important where the cost of energy is high or where plant is in continuous operation. Taking, for example, a 3-phase power distribution system in a factory operating on a 44-hour week, or 2 200 hours per annum, a p.i.l.c.s.w.a. cable used for main distribution may be rated in accordance with Table 17 of the Wiring Regulations, subject to compliance with voltage-drop requirements. An overall voltage drop of 7½% of the supply voltage is permissible, which on a 415-volt supply amounts to just over 31 volts between phases, and of this, perhaps 15 volts may be allocated for main distribution. Fig. 2 shows the I^2R losses in kWh per annum

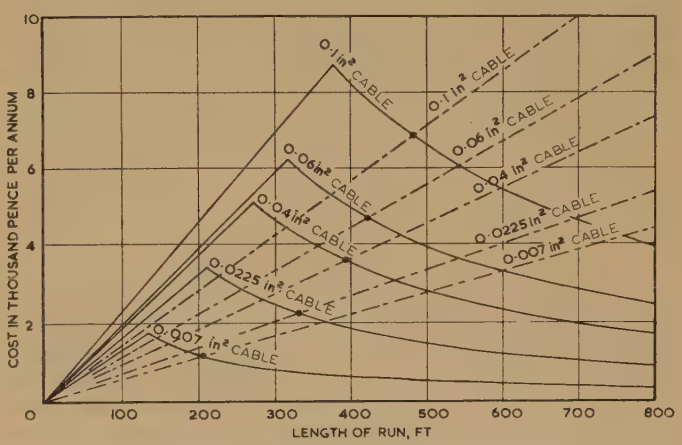


Fig. 2.—Running costs for various conductor sizes.
——— I^2R losses.
– — – Interest and depreciation.

plotted against the length of cable run in feet for various conductor sizes. From the top curve, which represents the losses in a 0·1 in² cable at 120 amp rating, it will be seen that these rise in proportion to the length of run up to the point where the voltage drop between phases amounts to the 15-volt maximum that is desired in this instance. Beyond this point the rating of the cable must be reduced as the length of run is increased so as to maintain the voltage drop at the 15-volt maximum, and here the heat losses are reduced proportionately with the square of the current derating but increased proportionately with length, giving the inverse characteristic that is evident. The other full-line curves represent losses in other sizes of cable similarly. If the cost of energy is 1d. per kWh, the ordinates beneath these curves will represent the cost of

heat losses in pence per annum. If we now consider the cost of these cables as currently quoted by the manufacturers, and assume that 15% of the original cost per annum is a reasonable allowance for interest and depreciation combined, this can be represented by the chain-dotted lines for each size of cable, the ordinates below which represent interest and depreciation in pence per annum. It will be seen that in all cases the cost of losses substantially exceeds that of interest and depreciation, up to the point where the full and chain-dotted lines for each cable cross. Where the cost of energy was less than 1d. per kWh, the cost of losses would be correspondingly reduced, but with longer hours of use, such as would occur with two- or three-shift working, these losses would be greater; a lower interest and depreciation rate would make the difference between the cost of losses and capital costs even greater. This will indicate the need for examining each case upon its own merits, when it may well be found quite uneconomical to rate such cables in accordance with The Institution's ratings based on temperature rise alone.

The effect of varying the rating of one particular size of cable, operating in similar circumstances, is illustrated in Fig. 3. The

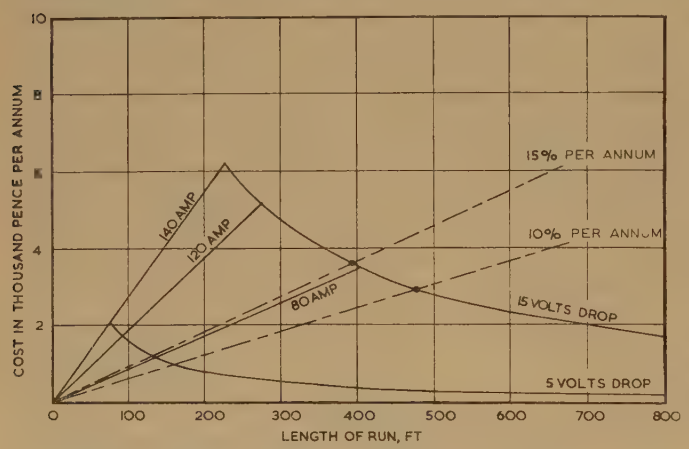


Fig. 3.—Effect of varying the rating of 0·04 in² cable.
——— I^2R losses.
– — – Interest and depreciation.

straight lines on the left represent the heat losses when this cable is rated at 140, 120 and 80 amp, respectively. The highest rating of 140 amp is taken from Table 22 of the Wiring Regulations, for underground cables, while the second, 120 amp, is the normal rating for the same cable installed indoors in free air. The right-hand curved portion represents derating corresponding to a limit of 15 volts drop as before. It will be seen that any load above about 80 amp is uneconomical on the basis of Kelvin's rule, in these particular circumstances.

If the cable is to be used for lighting or heating loads rather than a power load, the Regulations require that the voltage drop should not exceed 1 volt + 2% of the supply voltage, or just over 9 volts between phases. In such circumstances, it might be reasonable to allow 5 volts for main distribution, and the effect of this is shown by the lower curved line in Fig. 3. It will be seen that consideration of voltage drop takes precedence over Kelvin's rule as soon as a comparatively short length of run is exceeded, but this will not apply where voltage drop is compensated for by the use of automatic voltage regulators.

The need for greater flexibility in most industrial installations has led, on the one hand, to application of metalclad feeder bars and plug-in busbar systems, and, on the other, to greatly extended use of cable ducts and trunking and of perforated cable trays, in suitable circumstances. By the application of metalclad feeder bars for power distribution from the incoming supply substations in a factory, and the use of plug-in busbar distributors fed through fused connection boxes, it is possible to reduce substation switchgear to an absolute minimum and local power distribution centres can be virtually eliminated. The plug-in distributors afford facilities for connection of sub-circuits at any position, and can themselves be readily altered or extended to meet the ever-changing pattern of production requirements.

In trunking systems, only a small proportion of the total wiring space should be taken up with the original installation, for subsequently other cables will certainly be added; when overcrowded, the initial flexibility of the system becomes conspicuously absent. It is also well to note that, where conduits are to enter the side of a run of trunking, there is a minimum width of trunk corresponding to the minimum bending radius of the cable used, and that the larger sizes of cable, brought in at right angles, may block a considerable part of the cross-sectional area of a small cable trunk. Careful planning is also necessary where cable trays are used, but when this method is applied skilfully, extremely neat and orderly appearance can be achieved.

Time will not permit me to enlarge upon the many developments in types of installation cable now available, but the increasing use of mineral-insulated cables, and the rapidly widening application of p.v.c.-insulated armoured and p.v.c.-sheathed cables with their compact glands, have been very noticeable. I would also remark upon the saving in labour that can be achieved by the use of crimped solderless cable lugs for a wide variety of cable and flexible terminations. Already such lugs are used almost exclusively in the aircraft industry on account of their superior reliability when subjected to vibration and extremes of temperature. Since the necessary crimping tools are portable, they can be used as well on an installation site as in the factory, and it would seem that solderless lugs will replace sweated lugs as soon as their advantages become more widely recognized.

Standardization

Much as we appreciate what has been done during the post-war period, there is still considerable scope for standardization of dimensions of installation equipment and accessories. Notwithstanding the progress achieved in the development of the unit and cubicle types of switchboard, little attention appears to have been given to securing interchangeability even of the combined switch and fuse units of different makes, which could be of great advantage to those engaged in carrying out installation work oversea. Reference has already been made, elsewhere, to the urgent need for standardizing agreed sets of fixing dimensions for fluorescent-lighting fittings. I am sure that most installation engineers are aware of other instances where fixing dimensions should be standardized in the interest of the convenience of the ultimate user, noteworthy amongst which is the case of the ordinary electric-fire bar-heating element. In the field of plugs and sockets the industry still seems to be half-hearted in its approval of the 13 amp fused flat-pin plug; have we not yet reached the stage where 5 and 15 amp plugs to B.S. 546 should be considered obsolete, at least in new installations, as is now the case with 2-pin reversible plugs? Undoubtedly the time has come when we should agree to sink our individual preferences, and I earnestly look forward to the time when every domestic and office appliance will be sold with a B.S. 1363 plug moulded solidly to its flexible. Further than this, there appears to be an urgent need for standardization of plugs and socket outlets for exclusive use on 110-volt and 55-volt low-voltage

supplies, which are likely to be used increasingly in the future, as indicated in the paper presented four years ago by Mr. J. W. Bunting.[3]

On the credit side, real progress has been achieved in the standardization of fixings for lighting switches and the standard ranges of boxes now produced by some manufacturers. In the factory, we have at last secured standard specifications dealing with the fixing dimensions of foot- and flange-mounted motors, of both the ventilated and totally enclosed types, which should in years to come prove of very great benefit to every motor user.

Installation Design

The field of installation work is so wide that I cannot, as I am sure you will appreciate, do more than touch upon a few aspects that appear to be of present interest. Good results can only be attained by very detailed and advanced planning and careful site supervision; as much trouble as possible should be taken to make the work of installation simple and straightforward, for this will nearly always prove a very sound investment. Such considerations apply particularly in industry, where, for example, grouped motor-control panels are becoming a feature of modern installation technique. The use of these panels is most convenient where continuous processes or interlocking sequences are involved; in comparison with the alternative use of individual control panels, it may be said that, apart from the great improvement in general appearance, installation costs may be reduced substantially, and various interlocks and safeguards introduced that would not otherwise be easily attainable. It is, of course, essential that adequate and clearly marked means of isolation should be provided for each and every source of electricity supply brought into such a panel, so that maintenance work can be carried out in safety.

Speaking from the point of view of those in charge of maintenance, I should like to put in a plea for the clear marking of all important control panels and the provision of spare components, spare fuses and a clear circuit diagram within the panel enclosure. With such provision the engineer in charge need not hesitate to make the correct replacement in an emergency, without fear of needlessly interrupting a healthy circuit. For similar reasons, the internal wiring of control panels should be neat and orderly.

The multiplicity of functions requiring simultaneous control in many installations has necessitated the introduction of specially designed control desks to facilitate central supervision, especially where correlation of these functions is required. In his recent paper on 'Electric Control of Stage and Television Lighting', Mr. F. P. Bentham[4] showed how such lighting can be conveniently controlled from a compact lighting console. We have long been accustomed to mimic diagrams on control panels for switchboards, but now the same principles are being applied in industry for the remote control of complicated processes in plants extending over wide areas. For instance, in one large chemical handling plant all the main operations are supervised and controlled from a central station. Mounted on the supervisory panel are pushbuttons controlling the operation of the flow valves and conveyors, and lamps are used to indicate the position of valves, the direction of movement of conveyors and the state of repletion of the various silos, full or empty. Remote controls are provided for the mixing and grading of the material and for storage of the final product, and bells give warning to the operator if and when he fails to perform his function properly. In my view the application of central indicating and control panels of this kind could afford a very practical aid in the efficient operation of many large electrical installations, and could be applied with advantage in many industries as a means of improving productivity.

I believe that the installation engineer has a vital part to play in the future development of our industry, and that there is now a challenging opportunity for young men of technical and practical ability to develop effective careers that will bring work of great variety and consequence, and real pride in personal achievement. For graduates whose main interest lies in design and planning, there is ample scope in the field of consulting engineering, while others with administrative ability and powers of leadership may tend towards installation contracting, but, in either case, experience and training in installation work is necessary. The time has come when electrical installation work should be co-ordinated as a whole by those who can appreciate the technical and economic requirements of all the equipment and services that may be immediately and ultimately involved in any project. The supervision of regular inspection, maintenance work and repairs is equally important, and entails the service of qualified electrical engineers, and in fact the export of valuable electrical plant has on some occasions been restricted through lack of such services oversea. Electrical engineering is becoming of ever greater importance in all parts of the world, and wherever there is civilization there is useful work for the installation engineer.

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CENTRE, SUB-CENTRE AND GROUP CHAIRMEN'S ADDRESSES

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NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

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'REMARKS ON RESEARCH'

(ABSTRACT *of Address delivered at* MANCHESTER *7th October*, 1958.)

The past 25 years has witnessed a revolution in the utilization of mechanisms of all kinds to provide a continually improving standard of life for the community as a whole. The revolution has been particularly dramatic in the field of electrical engineering. The use of mechanisms is not only augmenting and largely replacing the physical labour aspect of human work; it is also, through the computer and its derivatives, augmenting and in some respects replacing the mental labours of the human brain.

This continuing increase in the availability and use of mechanisms presents many problems, both in general terms and in particular with relation to university education. Taking 'use' first, the implications of this aspect are obvious and have been frequently stated. If there are to be more mechanisms in use, there must be more scientists, technologists and technicians to manufacture and service them. Hence, of course, the current urge to expand the universities and technical colleges.

Increasing availability of mechanisms has two aspects—more of the same thing as before, and new things. New things appear so consistently that it is all too easy to assume that continued progress, and a continually improving standard of life, are part of the natural order of things. They are not. Progress requires that someone, somewhere, should do or make something that no one has done or made before. It may be a small thing or it may be very big, but, whichever it is, it is an exercise in originality. These various activities are covered by the broad title 'research', as it is used in academic circles, and it is in this sense that the term will be used here. In the world outside, research also includes at least one other activity, which may briefly be described as 'pulling the sales department's chestnuts out of the fire', an operation which is undertaken with some urgency when a sales department has sold something that the factory cannot yet produce. This activity is excluded from my definition, because research as I understand it, and as I have seen it in action in such places as T.R.E. during the war, is a driving force and guiding star, and not a straw to be clutched at by a drowning man.

Scientific research covers a very wide range all the way from purely theoretical extensions of higher mathematics to almost purely experimental investigation of properties of materials so complex in their structure as to be almost beyond the reach of theoretical investigation. Though the engineer is free to operate anywhere in the range, his natural home is towards the latter end, where he is firmly caught between the upper millstone of the laws of nature and the lower millstone of the properties of materials.

In this range pure science, essential though it is, is not enough. It must be allied with art, experience and a certain amount of low cunning. It is here that what I will call 'inventive research' has a major place; it spreads all the way from small design improvements to complex new devices or systems, such as jet engines, nuclear power stations and computing machines.

Every mechanism that currently aids our daily life springs from some basic invention in the past and subsequent more or less inventive improvements. Anything significantly new in mechanical aids in the future, and the continued improvement of existing ones, will require continuing inventiveness from someone.

Experience suggests that inventiveness is rare. There is a world of difference between learning how to do something that someone else can teach you, and discovering how to do something that no one else can teach you to do. The disparity is even greater if no one can even tell you what the something is.

This is because once a thing is known, or exists, it has so many links with pre-existing knowledge that it can be made to appear as a logical extension of that knowledge, but the probability is that the extension has been arrived at through only one link with the past, and that not the shortest.

Again, it is relatively easy to train a student to pass a particular examination, provided that the syllabus is pre-ordained and that there is available an adequate case history on the type of question the examiners are likely to set. The process is known as 'cramming', and properly done can produce from the student results which bear no relation at all to his real ability and most certainly no relation to his inventive capacity. The narrower the front the greater is the disparity. It is, however, a very different story if one considers how to train people to do things that have not been done before. Cramming is obviously impossible, the teacher himself does not know what in due course the student will originate.

It is a prime requirement of the educational system that it shall produce a continuing supply of people capable of original work. Such people are of particular importance to this country in its competitive struggle for economic survival, because ideas, suitably embodied in hardware, or suitably protected by patent law, are exportable. On the other hand, the raw material consumed in having an idea is negligible; the incremental fuel cost of intense mental effort has been estimated at one peanut per hour.

This, then, is the general background. It is a situation which obviously presents many problems to the university engineering departments, some of which have already been touched upon. The remainder of these remarks will be devoted to discussing the role of university research groups in this situation.

A research group is made up of a number of teams each comprising teaching staff, post-graduate students of all grades and technical assistants, each team being devoted to a different aspect of electrical engineering but housed in the same building as the undergraduates and open at all times to their casual inspection.

It might appear at first sight that a deep involvement in

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research by a member of the staff would detract from his value as a teacher by draining off a good deal of his energy and time. On closer investigation the reverse is easily seen to be true. A teacher may teach for, say, 40 years, during which period his subject will expand enormously. It is far better for him to keep up to date by being deeply engaged in the process of self-education by research than to attempt to do it purely as an act of duty.

A teacher is much more likely to infect his students with enthusiasm if he himself is so convinced of the importance and interest of his topic that he is prepared to spend most of his waking hours worrying about it. Furthermore, a teacher engaged in research is apt to be thrown back again and again on fundamentals in trying to solve his own problems. He is therefore more likely to emphasize fundamentals in his teaching.

From the viewpoint of the student the most frightening aspect of the situation is the continued expansion of the scope of electrical engineering.

A complete solution to this problem can never be found by extension of courses or the skilful rearrangement of their content. Even if time allowed it, such a course of action could only prepare him for the world as it is, not as it will be during the 40-odd years of his working life.

Much of what he later needs to know he will have to find out for himself, and a keen inquiring mind, coupled with the ability to apply fundamental knowledge to new situations, is far more valuable to him than any amount of specialized technical knowledge. In the development of these attributes the spirit that animates the teaching and the general atmosphere in which it is conducted are far more important than the content of the course. The teacher is in fact more important than the topic, and as has been indicated, research activity can help to produce the right type of teacher and to provide stimulating surroundings.

Again, the 'men of ideas' of the future will largely spring from among these students, which poses the question, How can people be taught to have ideas? The simple answer is, of course, that it cannot be done. All that can be done is to select people with natural ability and encourage them, by exposing them to an environment in which original ideas are regarded as important things, for which credit and standing and advancement can be obtained. Originality, like measles, is contagious, but again like measles, it will only be caught by those susceptible to it.

The development of originality is made difficult at under-graduate level by the examination problem, and the difficulty is aggravated if the examinations are set externally on a pre-ordained syllabus. Inevitably the chief concern of the student is to pass the examination, and since the answers to questions set to a fixed syllabus are known, the student's best bet is to learn those answers rather than attempt an original solution, for originality and certainy can never go hand in hand. Even so, a stimulating teacher teaching in his own field of interest, and given as free a choice of his subject-matter as circumstances will allow, can do a great deal.

It is, however, at the post-graduate level that a flair for originality can be given its first real chance, by associating the student with some research activity, and by replacing the examination bogey by the requirement that he shall be able to demonstrate, by writing a thesis, that he has a grasp of the essentials of some unsolved problem, and has applied his talents to assisting in its solution. He is brought up sharply against the fact that he will not always be able to get the solution to his difficulties by asking someone to tell him the answer, or by studying a textbook. What he has learnt ceases to be something he needed to know to satisfy examiners, and begins to be forged into a tool with which he can lever out new information for himself.

There are, of course, many places outside the universities where post-graduate training in research can be obtained, but one great advantage of university research is that activity is not confined to a particular sphere, nor is it necessarily directed towards a fixed objective. It is free to take the line of least resistance and to exploit any break-through, no matter where it may lead.

Thus, a strong research school with several different lines of interest is not only necessary to provide facilities for the post-graduate student to develop his talents, it can also exert a beneficial effect on the undergraduate school on both sides of the lecture bench. In addition, of course, there is always a chance that something really useful will come out of the work. The chance of something useful emerging and of being actually used is greatly increased if close and informal links can be formed with industry, preferably local industry. Collaboration in research effort is probably the best way of maintaining and expanding the close contact with industry that is so important to the future of engineering education.

To summarize: university research in engineering can provide valuable contributions in at least five ways:

(i) By extending the boundaries of knowledge.
(ii) By keeping the staff lively and up to date in their own speciality.
(iii) By demonstrating to the student the dynamic nature of the subject and encouraging a flexible approach to it.
(iv) By providing an atmosphere in which the student can develop any talent he may have for original work.
(v) By tightening the links between industry and the universities and increasing their mutual understanding.

The first objective is well known; the others may be less widely appreciated, outside academic circles, and yet they may be more important in the long run, because the boundaries of knowledge, particularly in engineering, can be, and are, subject to continual expansion outside the universities. Furthermore, much of this expansion can only take place outside the universities because of its scale or its direct application to production. It is therefore important at all times to ensure that contribution (i) does not predominate; the project must not assume overriding importance at the expense of its usefulness as a vehicle of education. For similar reasons, the development of a separately staffed post-graduate research school, though it may accelerate the extension of the boundaries of knowledge, is almost certain to do so at the expense of the stimulation of undergraduate teaching.

From the point of view of the indirect benefits of research, (ii)–(v), the importance and success, or otherwise, of the work undertaken is not a prime consideration, but there is, of course, nothing quite like a resounding success to heighten morale.

By way of conclusion, two examples will serve to illustrate these and other aspects of university research.

The Electrical Engineering Department at Manchester contains what is probably the most potent computing organization in any university in this country. It provides a nation-wide computing service covering a very wide field of interest, mainly far removed from electrical engineering.

If the history of this apparently illogical but highly successful development is traced back, it is found to depend, not on any deliberate preplanned policy, but on a series of fortunate accidents coupled with freedom to pursue what appeared to be the most profitable course at any particular time without paying too much attention to where this might ultimately lead. Thus, the original impetus came from work on storage systems, during which a particular, somewhat fortuitous and ultimately irrelevant, experimental observation can be clearly identified as the turning-point between failure and success. A computing-machine store can be thoroughly tested only by using it in a computing machine, so a small computing machine was built. It worked, and close collaboration with local industry began.

A commercially built computer was installed in the University to gain operational experience to guide future research in machine design. Its appetite was insatiable, so it was made available to outside users. Meantime, improved machines were being designed in the Electrical Department proper, and the engineering and operational aspects of computing machines continue to develop side by side.

The effect of all this on the light-current side of the departmental activity has been, and still is, extremely stimulating; close links with industry have been formed, and a contribution to progress has been made.

The glamour of radar, and later of computing machines, was at one time tending to unbalance the Department in the direction of light-current work. Fortunately, one of my colleagues with a knowledge of textile machinery decided to examine the possibility of electrical shuttle propulsion. For this purpose he built a long linear induction motor designed to move conducting material along a straight line instead of round and round. This novel device excited considerable interest in the Department, and gave rise to many questions which could not be immediately answered. In particular, it posed the question, What would happen if the conducting material were constrained so that it could move only in a direction other than the direction of motion of the magnetic field? From this bit of idle curiosity there has grown up a considerable research effort concerned with the development of brushless variable-speed induction motors, which has already met with some success and has brought another close and valuable contact with industry. It has also revitalized the teaching of heavy electrical engineering and has corrected the balance of interest in the Department.

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NORTHERN IRELAND CENTRE: CHAIRMAN'S ADDRESS

By D. S. McILHAGGER, M.Sc., Ph.D., Member.

'THE INSULATOR SURFACE'

(ABSTRACT *of Address delivered at* BELFAST 14*th October*, 1958.)

In the early days of our electrical engineering studies we were told to imagine a man swimming along a conductor in the direction of the current. Most of us thought this a bit odd at the time, but we accepted the suggestion and the whole thing left a profound impression on us. I trust, therefore, that you will forgive me if I ask you now to imagine another man, submicroscopic in size, making a journey from the body of a homogeneous solid, through the surface, to the body of a homogeneous gas in contact with it. This man, if he is observant, will pass through a bewildering variety of experiences, to some of which I want to draw your attention, for they are vitally important to us as electrical engineers.

At the beginning the journey will undoubtedly be monotonous, but when our scientific observer comes close to the solid surface (perhaps a millionth of an inch away from it), the solid through which he is travelling begins to change its nature and this change develops as the journey proceeds. At the surface itself, which is as craggy as Greenland's icy mountains, he will pass through a very thin layer of crust, only one molecule thick, which is a chemical combination of solid and gas. Beyond this, he may encounter a layer of liquefied gas of up to a millionth of an inch in thickness before he reaches the gas itself. The gas changes in nature as he proceeds, until finally it, too, can be said to be homogeneous.

A physicist might tell us that from the beginning to the end of this journey the man would meet nothing but electrical particles of one sort or another. While this is probably true, and very satisfying to the ego of the electrical engineer, it does not emphasize the complexity of the surface, so we will forget about electrical particles. We cannot, however, forget about ions—molecules which are positively or negatively charged—for on his journey our observer would pass through several layers of such, so that he could be regarded as travelling up and down electrical potential gradients as on a switchback. He will certainly finish up at a potential different from that at which he started.

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The journey has shown us that the transition from solid to gas is not instantaneous and that the surface is neither simple nor of zero thickness. Let us leave our observer there, for he has served his turn and is almost certainly too exhausted to help us further.

From the nature of electrical circuits it is nearly impossible to separate conductors by solid insulators without leaving some exposed insulator surface-paths between them. In some cases, as in cables, these surface paths only occur at the ends, where they can be neglected or adequately dealt with. In other cases, however, and the so-called 'air-insulated' overhead transmission line is one of them, each conductor must be supported at intervals on solid insulators, the surfaces of which are exposed to the atmosphere. When there is a potential difference between the conductors—and that is what they are there for—these surface paths have considerable nuisance value, especially if they are contaminated. The major part of line leakage conductance is due to the ionized layers at the interfaces between the solid and gaseous insulators; and the major cause of power supply failure is the breakdown which takes place over, or follows closely, a solid insulator surface. As one writer[1] aptly says '. . . surface leakage currents caused operating difficulty in the infancy of power transmission some eighty years ago . . . and exist to-day as one of the few remaining service problems'.

In the design of an insulator, as in the design of anything, the engineer must first select a suitable material and then mould or hew it into such a shape that its good features are used to the best advantage while its bad features are not unduly obtrusive. In the selection of insulating materials for a particular application the electrical engineer is confronted with a myriad of properties—physical, chemical, mechanical and electrical—and he must give due weight to each before making his choice. In a given case the problem is simplified by the fact that many materials are completely unsuitable under one or other heading. For example, glazed porcelain, despite its somewhat unattractive surface properties, was regarded for many years as the only material suitable for transmission-line insulators. More recently, tough-

ened glass has offered strong competition, and impregnated hardwood has been suggested[2] but, so far as I am aware, has not been used. Despite the enormous variety of insulating materials available, including many synthetic substances developed over the last few decades, it is perhaps not surprising that the materials suitable for this job are so few when one considers the arduous conditions under which line insulators work.

Many factors, too, determine the ideal shape of an insulator. It would be a happy design which achieved anything like a uniform potential gradient over the surface under varying surface conditions. It would be happier still if any part of the surface could be really protected from the contaminating effects of atmospheric pollution. Unfortunately, the insulators available fall far short of these ideals, but we can perhaps be thankful for their good points. They must hold the conductors up, and this they do with astonishing reliability. They maintain, over long numbers of years, their high 'body' insulating properties. Also, provided the atmosphere is reasonably clean, they can have such a length of surface leakage path as to give reasonable freedom from surface trouble.

Let us consider one well-known suspension insulator unit, the cap-and-pin type: the upper surface is short and the lower (and so-called 'protected') surface is long and tortuous. This type of insulator has been illustrated in textbooks for over thirty-five years, and it may be assumed to be much older than that; but, virtually unchanged to-day, it is so widely used that it is regarded by many engineers as the only type worthy of consideration. All the problems introduced over the years by the use of higher and higher line voltages and the long-term effects of atmospheric pollution (also increasing) have been met by the use of more and more units per string, together with taller and taller pylons. This is not to say that other types of insulator have not been suggested or indeed tried,[3,4] but owing partly to the resistance of the user to change, and partly to the economic impossibility of offering new types, in small demand, at the same price as an almost universally used type, the fact remains that the cap-and-pin insulator will be hard indeed to dislodge.

A strange feature of the cap-and-pin insulator is that, although it was designed to provide long protected and short exposed surfaces, it appears to work even better with all its surfaces exposed, for, as A. D. Lantz[1] puts it: '. . . the strain position arrangement has the triple benefits of improved drip clearance, accessibility of all surfaces for natural cleaning and the acquisition of sufficient space to allow radical changes in leakage distance'. This surprising claim, substantiated by other workers, follows a severe but naïve criticism of those engineers who are rash enough to experiment with new types. We might ponder over those three benefits, for they suggest strongly that a new approach to insulator surface design is overdue.

Three factors have arisen in recent years which must drive the power engineer to tackle the whole problem of line insulation afresh. First, existing high-voltage lines, such as those of the British 275 kV Supergrid, will require in the foreseeable future to have their voltages increased: this will be economically possible only if the new voltage can be accommodated on insulator strings having no greater overall length than those now in use.[5] Secondly, the expanding use of high-voltage d.c. transmission by overhead lines raises a host of new problems such as the control of voltage distribution over insulator strings, the effects of electrolysis on voltage distribution over the surfaces of insulator units and on corrosion of the metal 'hardware'. A third factor, and probably the most compelling one, is the increasing dirtiness of both urban and rural atmospheres, caused by the ubiquitous Diesel engine, aerial crop spraying, road dust and a great number of messy industries. Near one cement works, not a thousand miles from here, overhead-line insulators require, once a month, to be hand cleaned with acid, and in bad cases contamination must be literally chipped off the surface. This problem could and should be solved at the sending end.

As a basis for new insulator design the engineer must fall back on the published results of research workers, and if these are insufficient he must pursue such applied research as will provide him with the necessary information. It has been correctly said that the only outstanding problems of line insulation are those of insulator surface behaviour, and an enormous amount of work has been done and a staggering quantity of literature published on these very problems. I think it would be fair to suggest, however, that these researches are largely uncorrelated. Chemists and engineers engaged on surface study appear, not only to work in different laboratories, but to use the journals of different learned societies to publish their work (even the Faraday Society, which deals with electrochemical problems, is not supported, as it should be, by electrical engineers). No single abstracting body covers the work of both, so that it is possible for one to be completely ignorant of the many valuable contributions of the other. Two examples, which are certainly not isolated cases, will illustrate the point. In a magnificent textbook on the physics and chemistry of surfaces, N. K. Adam[6] makes—so far as I can find—only one reference to the existence of electrical engineers, in the sentence, 'The conductivity of surface films of adsorbed moisture may be a serious trouble in high-voltage engineering practice'. Similarly, in a comprehensive survey of the behaviour of transmission-line insulators working under unfavourable atmospheric conditions, Zanobetti and Vischi[7] give 93 references, not one of which is to the publication of a chemical society. I hope and believe that this state of affairs will not long continue, for the engineer has much to learn from the chemist, and, I might add, much to teach him.

Too much of the research work of engineers assumes that existing insulator types are, if not perfect, at least the best likely to be available. Even with new d.c. lines there is no indication that special insulator types are being developed to deal with the very real problems of contamination and electrolysis peculiar to these lines. Recent utterances of Russian and Japanese workers[9] imply that d.c. transmission introduces no additional problems, although time may tell a different story.

As to the future, there are three ways in which the problem of insulator surface breakdown can be tackled. Insulators may be designed—or existing designs may be modified—which will accept contamination and fog without breaking down. Conducting glazes, water-repellent surfaces and water-repellent coatings such as silicone greases are present-day examples of this approach. A second and better way would be to design insulators which will reject contamination from their surfaces. This has been attempted for a.c. lines, and with some success, by the use of suitable electrostatic shields.[8] Conducting glazes, by keeping the surfaces warm, also keep them cleaner and freer from condensation. A third and very useful approach to the problem would be to attack contamination at the source, i.e. to investigate the causes of atmospheric pollution and to seek, by education and legislation, to put a stop to it where this is humanly possible and not merely economically feasible. There is a growing public awareness that atmospheric pollution is a social evil, and it is our responsibility, as electrical engineers, to foster and nurture that awareness. The very insulators which we wish to protect from atmospheric pollution carry the power lines which could enable that pollution to be abolished.

We can build power stations, and the public will, by and large, hate the sight of them. We can erect high pylons, and the

societies for the preservation of this and that will oppose us every inch of the way-leave. If we ask for cleaner air, however, we are for once on the side of the angels, the medical men, the law-makers and that great unpredictable—the man in the street. Let us ask for cleaner air and ask for it continually and with high-raised voices. At the moment, to throw a piece of paper on the pavement may attract a fine of £5: to 'discharge sewage into the atmosphere' (as one person graphically described it recently) attracts nothing but mild criticism, unless the effluent is as black as the soul of the one who is responsible.

Finally, it is no use trying to convert other people if we ourselves are not above reproach. There is more than one reference in the literature to the effects of effluent products from generating stations on the contamination and breakdown of insulators. Let us swallow our own smoke before asking others to swallow theirs.

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WESTERN CENTRE: CHAIRMAN'S ADDRESS

By R. W. STEEL, Member.

'SOME PROBLEMS AND PROSPECTS OF THE ELECTRICITY SUPPLY INDUSTRY'

(Abstract *of Address delivered at* Bristol 13*th October*, 1958.)

To-day, more than ever, the young engineer can look forward to occupying a managerial post, provided that his outlook and knowledge are sufficiently broad. This address therefore deals with matters other than engineering and is directed towards those who have entered the electricity supply industry more recently, as well as to those outside it.

A District Manager's first duty, as I see it, is to ensure that the Board's staff operate efficiently and harmoniously, and that all sections are properly balanced. Consumer relations and public relations must both be maintained—and by public relations is meant those with M.P.'s, Municipal, Urban and Rural District Councils, the National Farmers Union and other bodies who seek to influence Board policy. This is best done by the widest possible personal contact. Because we are nationalized, the public are more prone to criticize, particularly as they feel we are dealing with 'public money'. There is much misconception over this term: surely it can only mean that which is levied, such as rates and taxes, and for which nothing specific is received in return. The revenues of the nationalized industries are not obtained in this way; they are derived from the sale of goods, services or energy which the public are free to take if available, or refuse to take, and the transaction is just as commercial as the sale of a pound of sugar over the grocer's counter. No one would claim that the grocer's takings are public money, although it all comes from the public.

The public expect detailed explanations on any matters they may raise, and the Boards must treat complaints much more seriously than would private businesses. This 'public accountability' of nationalized industries places a heavy burden on them. The public also expect uniformity of treatment all over the country, and to try to do this requires a great deal of co-ordination, resulting in much paper work and increased administration costs. In addition, there are the requirements of both internal and external auditors, which often means introducing safeguards and procedures which private industry is at liberty to modify or dispense with.

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One of the reasons why various industries were nationalized was to ensure that employees felt that they played a part in its management. Accordingly the Electricity Acts laid this duty on the industry and two sets of machinery have been set up, one for negotiating terms and conditions of employment, and the other for promoting health, safety, welfare, training and efficiency. The manager's part in this work is most important: he cannot deal with staff problems as he could with an engineering problem, for human reactions involve emotions, and to paraphrase a well-known saying, when emotion enters the door, logic flies out of the window. Managers should encourage free discussion and make sure that those elected to serve in the consultative machinery feel they are doing a worth-while job. I am sure this is so in the electricity supply industry, and if the same methods were followed elsewhere there would be less industrial strife. As an example of the seriousness with which the Boards take their duties, I may mention that no fewer than 42 500 employees have been sent on residential training courses since 1949, i.e. one in four of the total employees.

Many of our difficulties are caused through external control of capital expenditure. The Treasury allots a share of the country's estimated available capital, schemes are prepared, prospective consumers are notified and construction schedules completed. Then when everything is geared and moving at the new tempo, a financial crisis is followed by a directive to cut capital expenditure. What this means to efficiency, to management and to the prospective consumers can well be appreciated. Perhaps some alleviation could be made by allowing us to achieve our capital expenditure targets taking one year with another in the same way as we do our trading results. The present rate of capital investment is half our total revenue and is well over £1 000 per employee per annum. With the load doubling at least every ten years, the amount of new plant, the amount of replacement and reinforcement must grow year by year. If this new work is not done, if replacements and reinforcement are not provided, chaos must ensure. Voltage regulation must be maintained more closely than in the past—if only

because of its obvious effects on television sets. The trend of load growth cannot be halted by restricting connection of new consumers, for there are already practically 15 million being served, who can only be controlled by cutting them off—and that is unthinkable.

One of our principal duties is to distribute supplies to those who may require them. In urban areas it is only practicable to do so by underground cables, but in rural areas we have an alternative. As voltage increases, the ratio of cost of underground cables to that of overhead lines increases until at 275 kV it can soar to 12 : 1. Few consumers who need a supply object to being served via overhead lines, but often those not immediately concerned bitterly complain that amenities are being spoiled, quite overlooking that another amenity, perhaps the greatest of them all, is being created. Our engineers do take great care to meet objections, and much negotiation is done before the schemes become public. One's ideas on what is an amenity change according to one's needs and viewpoint, and I like to think of steel pylons as knights in armour, who are striding across the countryside to fight for a very much higher standard of living for us all.

Under the 1947 Electricity Act, the Boards (not the C.E.A.) were charged with the duty of cheapening supplies. We little thought then that we were about to go through an inflationary period, but despite that the price per kWh has risen by only 44·2% since 1938 and 34·1% since 1948. In the South West the Board's costs per kWh rose by only 1·8% between March, 1949, and March, 1958, while bulk-supply costs rose by 45% despite the annual load factor rising from 41·6% to 45·79%. Electricity has become relatively cheaper compared with gas and oil, as shown in Fig. 1. Undoubtedly this trend will continue.

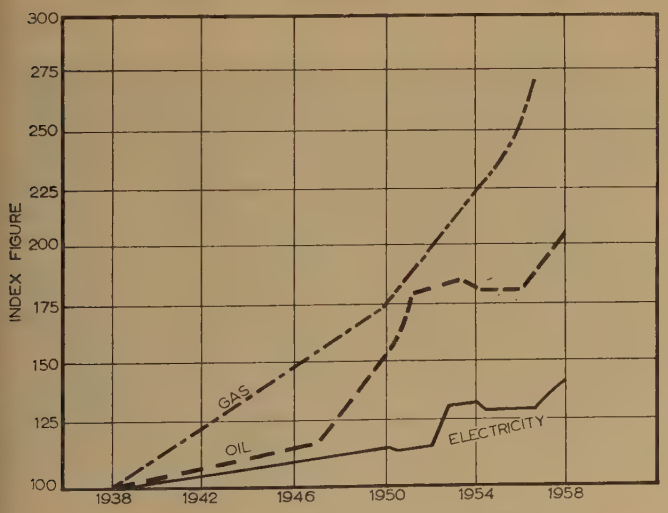


Fig. 1.—Relative prices of gas, oil and electricity.

The best way to reduce average prices is to improve the load factor. Reluctance to adopt factory shift working operates against us, but fortunately many new factories using large quantities of electricity have continuous processes with relatively few employees. Storage heating is now being developed in commercial premises and small factories, while floor warming is coming into use. These developments promise to bring us large loads if the right tariffs can be offered.

Nothing damages public and consumer relations more than interruptions of supply, and even planned interruptions, notified to consumers in advance, for maintenance purposes or connecting up new lines, must be minimized. Duplicate lines and plant are too costly to provide, but careful planning, timing and selection of equipment can keep outages down. Increasing use of 'live line working' and greater use of mobile generating sets reduce the number of planned interruptions, whilst greater use of high-speed auto-reclosing circuit-breakers is enabling supplies interrupted by faults to be restored more quickly. Formerly, when switches in unattended substations tripped out we had to rely on notification by an affected consumer. Now auto-call systems immediately dial the district office when a switch trips and transmit from a wax disc an appropriate message.

Boards also carry out sales of fittings and apparatus, and undoubtedly pioneer work by companies and municipalities in selling and servicing electric cookers, for example, has made this form of cooking popular. The selling and service of cookers is an expensive business which can be done successfully only on a large scale. Had the business been spread over a large number of relatively small firms it could never have become profitable, and the change-over to electrical methods in so many directions by the housewives of this country would have been much slower. Boards have also carried out a great deal of testing in addition to that done by the Electrical Development Association, thus improving the efficiency and safety of appliances marketed. A natural development was for Boards to carry out wiring installation work, so that they could find out the difficulties for themselves and set a high standard, as it is their duty to see that wiring installations connected to the mains are free from shock and fire risk. The competition offered to private contractors is not serious, but is complementary, and generally there is close co-operation between Boards and contractors, which in some districts is not only helpful but cordial. We are all in the electrical business together, and the more we help each other the greater will be the prosperity of the whole industry.

Such is our rate of growth that very soon sufficient coal will not be available, and oil supplies may prove both unreliable and costly, so we can only rely on atomic energy. Although expensive to build, atomic stations have remarkably low running costs, which Sir Christopher Hinton forecasts will drop to 0·1d. per kWh by 1990, while conventional running costs will tend to rise, as shown in Fig. 2. Total nuclear costs should equal conventional station costs by 1962, whilst by 1967 total nuclear costs should be less than conventional running costs. Off-peak consumers cannot expect to have electrical energy at this low figure, as they must contribute towards fixed costs, but what an extraordinarily wide margin there is between the running costs

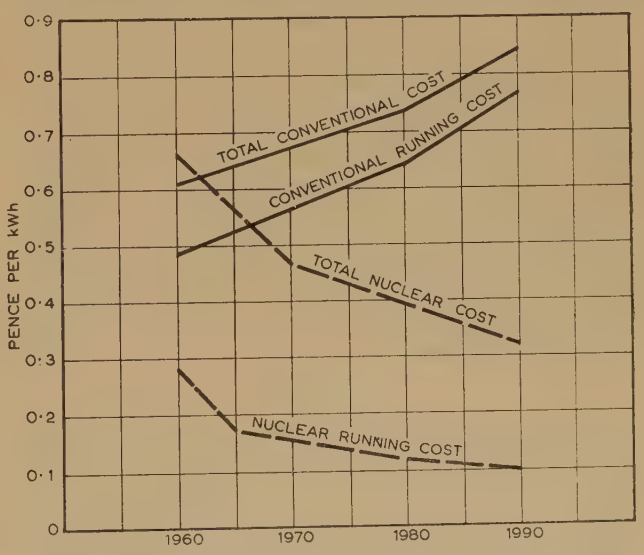


Fig. 2.—Relative costs of nuclear and conventional generation.

of the two different types of station! This margin should permit development against any competition, and it seems incredible that any substantial building should be erected in future without some form of electrical storage heating. Already groups of houses for private sale and occupation are being built with floor warming. There are 50 million ft^2 of industrial buildings being erected and 270 000 houses being completed every year. Allowing only 10 watts per ft^2 and 3 kW per house, the additional load for these alone would be 1 300 MW per annum if electric storage heating was adopted. There is also enormous scope for heating water during off-peak periods by fitting larger or auxiliary tanks. This load would be doubly valuable, as it would reduce the peaks and is required also in summer time. All these factors are cumulative, and they would augment revenue and put the industry in a position to do more self-financing, and make electricity cheaper not only relatively but actually. The industry must not be hampered by the 'undue preference' clause in providing suitable tariffs for night loads which will benefit the industry as a whole, as the maximum use must be made of the nuclear stations. If tariffs are framed with vision and boldness, the way will be open for hitherto uneconomic industrial processes to be developed, and enormous amounts of energy could be used in agriculture for increasing food output.

The path which lies ahead for those who guide the electricity supply industry is not an easy one. Tremendous and far-reaching decisions will soon have to be taken in order to ensure that the industry is on the right course and travelling at the right speed, and all those who manage the industry will not only need a wide experience in psychology applied to the arts of management and salesmanship, but will also be the better fitted for their task if they have had a sound engineering training and experience.

Many people think that the success of an industry should be judged by the financial result at the end of each year, but I feel, from such experience as I have had, that there is a lot more to it than that. The industry in which I have the privilege to serve must not only provide cheap energy at an economical price, backed by sound service, but in doing so, it must make its consumers well content, and make all its employees feel that they are doing a very worth-while and satisfying job. I hope that we in the South West can justly feel that we are playing a leading part in achieving these ideals.

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SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By R. J. RENNIE, B.Sc., Member.

'THE DEVELOPMENT OF THE ELECTRICITY SUPPLY INDUSTRY IN SCOTLAND'

(ABSTRACT *of Address delivered before the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *7th October, the* SOUTH-WEST SCOTLAND SUB-CENTRE *at* GLASGOW *15th October, and the* NORTH SCOTLAND SUB-CENTRE *at* DUNDEE *16th October, and* ABERDEEN *17th October*, 1958.)

With the advent of atomic energy the electricity supply industry stands on the threshold of a new era. It is appropriate, therefore, to review the past 60 years since public supplies of electricity first became available in Scotland. It was early recognized by Parliament that some regulation of public supply would be essential; thus the growth of the industry from its inception has been profoundly influenced by legislation.

The Electric Lighting Act, 1882, which was the first measure dealing with electricity supply, enabled local authorities, companies or persons to be granted provisional orders to supply electricity within defined areas and for specific periods, after which company or privately owned undertakings could be purchased by local authorities. Little encouragement was given to large-scale enterprise, and many small undertakings were set up each with its independent power station. During the early years of the present century, Parliament passed a number of Acts under which power companies were set up with perpetual rights to supply electricity to industrial consumers and to authorized undertakers.

1890–1919

The first public electricity supply became available in Scotland in 1892, when the Corporation of Glasgow purchased the undertaking established in 1880 by Muir and Mavor, supplying 37 consumers from 300 kW of generating plant. By 1896 electric lighting orders had been granted in 7 burghs, comprising 40% of the total population of Scotland, and by 1916, 67 burghs had been included under electricity orders, covering 60% of the total population, of which only 15% were included under orders granted to companies.

Prior to 1905, only the burghs of Ayr and Paisley generated and distributed alternating current (Fig. 1). All other undertakings generated direct current, usually 3-wire, at voltages varying from 115/230 to 250/500 volts. The initial prime movers were Willans or Bellis vertical reciprocating steam engines, and the generator ratings varied from 23 to 400 kW. Lancashire boilers were soon superseded by drum-type water-tube boilers, and by 1905 chain-grate mechanical stokers, superheaters and economizers were being installed.

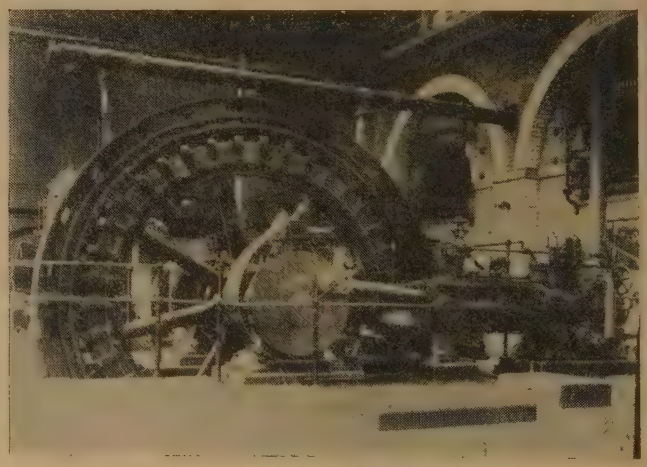


Fig. 1.—Alternator at Mill Street, Ayr.

Boiler ratings varied between 17 000 and 20 000 lb of steam per hour at pressures varying from 160 to 225 lb/in^2, and temperatures from 500° to 700° F. Two of the early power stations were abandoned as too small after only ten years' operation.

In 1905 the first turbo-alternators were installed. These were

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3-phase 25 c/s 1 500 r.p.m. machines, those in Glasgow being rated at 3 MW 6·5 kV, and those on the Clyde Valley Electrical Power Co. system, at 2 MW 11 kV. When 3-phase 6·6 kV supplies were introduced some years later at Edinburgh, Dundee and Aberdeen, the frequency adopted was 50 c/s. A 5 MW set installed in 1910 had a steam consumption of 12·8 lb/kWh at 29 in (vacuum) with steam at 225 lb/in^2 and 700° F.

During the 1914–18 War, the demand for electrical energy increased so rapidly that the maximum demand on the Clyde Valley 11 kV system rose from 14 MW in 1915 to 27 MW in 1916. The site of Clyde's Mill generating station was surveyed in August, 1915, and by November, 1916, the first 5 MW set was on load. This was a remarkable achievement under conditions of such acute shortage of labour that women were employed as labourers on the construction work.

Many of the early distribution circuits consisted of bare copper bars carried on porcelain insulators in ducts or culverts. Although the supporters of this system pointed out that the current-carrying capacity of the circuits could readily be increased by the addition of copper bars, it was very soon superseded by cables. Cables insulated with jute, hemp and vulcanized bitumen were drawn into pipes or laid in troughing filled with pitch.

Triple concentric 1 in^2 lead-covered cable, of 3½ in diameter, manufactured in 1899 for Glasgow Corporation is believed to have been the largest cable then made anywhere in the world. Paper-insulated lead-covered steel-wire-armoured 3-core 6·5 kV cables were first laid in Glasgow in 1903, and from 1905 onwards underground cables and overhead lines operating at 10 kV were used in the establishment of the Clyde Valley system.

1920–1947

The Electricity Supply Act, 1919, set up the Electricity Commissioners charged with promoting, regulating and supervising the supply of electricity. The Electricity Supply Act, 1926, set up the Central Electricity Board to concentrate the generation of electricity at a limited number of selected stations, to interconnect stations by a transmission system, to standardize frequency at 50 c/s and to supply electricity to authorized undertakers. These two measures accelerated the tendency towards fewer and larger generating stations and higher distribution voltages.

The first section of Dalmarnock generating station, which was commissioned in September, 1920, comprised five 18·75 MW 25 c/s generators directly connected to 6·5 kV/20 kV transformers. The boilers were rated at 50 000 lb/hour and supplied steam at 250 lb/in^2, 650° F. By 1926, Dalmarnock had been extended by two additional sets, and with its annual output of 209 million kWh, ranked fourth in Britain. In 1937, two 50 MW 20 kV generators and six 200 000 lb boilers had been added, and the steam conditions raised to 600 lb/in^2 and 825° F. Portobello generating station, which was commissioned in 1923, at first comprised three 12·5 MW 50 c/s generators; later additions of 30 MW sets increased the station capacity to 146·5 MW by 1939.

Britain's 132 kV Grid system, now the largest interconnected transmission system in the world, was initiated when the first section of the Central Scotland scheme was energized from Bonnybridge generating station in April, 1929. By 1931, thirteen 132 kV substations with an aggregate transformer capacity of 725 MVA and 240 miles of 132 kV overhead lines had been completed. In 1947 the Grid system in Scotland comprised 690 circuit-miles of overhead lines and 1 296 MVA of transformers.

The formidable task of conversion from 25 to 50 c/s of the Glasgow Corporation and the Clyde Valley Electrical Power systems was started in 1928 and completed in 1933. While this work was proceeding it was commonplace to have both frequencies in one substation, but from first to last no mishap occurred. The magnitude of the conversion is illustrated by the following items of equipment converted or replaced; 16 generators totalling 221 MW, 230 rotary convertors totalling 182 MW, 18 970 motors amounting to 340 353 h.p., and about 430 000 meters.

The most significant development in the distribution of electricity to the countryside took place in Dumfries County, where supplies to the rural community became available from 1933. Three-phase 33 kV and 11 kV main lines were constructed, to which were connected 11 kV single-phase spur lines supplying small rural communities and farms. By 1946, 11 000 consumers, representing 73% of the number of potential consumers in the area, had been connected.

As long ago as 1903, a Canadian firm of engineers reported on the possibility of producing power from the Falls of Clyde, but it was not until 1927 that the project was completed by the construction of two stations with a combined capacity of 15·5 MW, the 4·92 MW 25 c/s generators being the largest hydro-electric sets then in operation on any public supply system in Britain. Between 1931 and 1936, the Galloway Water Power Co., established in 1929, completed a hydro-electric scheme comprising 5 generating stations and 7 reservoirs. The total installed capacity is 105 MW, and the average annual output, 230 million kWh. The Grampian Electricity Supply Co. obtained statutory consent in 1922 to the construction of hydro-electric generating stations at Rannoch and Tummel, and in 1930 the first of three 16 MW sets was commissioned at Rannoch. Following six unsuccessful attempts by companies to obtain the consent of Parliament to hydro-electric development in the Highlands, the North of Scotland Hydro-Electric Board was established by Act of Parliament in 1943.

Experience during the Second World War emphasized, not only the national value of the integration of electricity supply made possible by the establishment of the Grid, but also the need for larger distribution areas. Following another examination in 1945 of the problem of the co-ordination of electricity supplies throughout the country, Parliament passed the 1947 Act nationalizing the industry.

1948–1958

On the 1st April, 1948, forty-four separate undertakings in Scotland were reduced to four, namely the Central Electricity Authority (represented by the South West and South East Scotland Divisions) and the South West and South East Scotland Electricity Boards, responsible to the Minister of Fuel and Power, and the North of Scotland Hydro-Electric Board, responsible to the Secretary of State of Scotland, for developing and maintaining an efficient, co-ordinated and economical system of electricity supply. This arrangement continued until 1st April, 1955, when, under the Electricity Reorganization (Scotland) Act, 1954, the South of Scotland Electricity Board became responsible to the Secretary of State for Scotland for the generation, transmission and distribution of electricity in the South.

From 1948 to 1952, generating plant was so inadequate that load shedding by switching out h.v. feeders occurred on 79 days and for a maximum continuous period of nine hours. Supplies to essential consumers such as hospitals and collieries were maintained, and a rota system was worked out to ensure equitable sharing of the inconvenience of loss of supplies among the other classes of consumers.

Since 1948 only two new steam stations have been completed in Scotland. Braehead, which was completed in 1953, comprises four 50 MW generators. Barony, containing two 30 MW generators commissioned in 1957, is the first public generating station designed to burn washery slurry. Following modifica-

tions to the fuel-handling and drying machinery, the boilers are now burning 98% slurry. Three 60 MW sets were installed at Portobello, and in 1954 and 1955 the first of these sets, which operate at 1 350 lb/in^2 and 950° F, achieved a thermal efficiency of 31·53%, then the highest in Britain.

In 1948 the total installed hydro-electric capacity in the North of Scotland Board's District was only 87 MW, and by 1957 it was 729 MW. The largest public hydro-electric generating station in Britain is Loch Sloy, in which four 37·5 MW sets were commissioned in 1950; and the largest hydro-electric generator on public supply is the 40 MW set commissioned at Clachan in 1955. During the ten years ending in 1957, the Board have constructed 143 miles of tunnels, and in 1955 they created a world record by driving 557 ft in one week.

In 1948 there were only 690 circuit-miles of 132 kV overhead lines and 1 296 MVA of 132 kV transformers in commission in Scotland, but by 1957 these had increased to 2 222 circuit-miles of lines and 3 320 MVA of transformers. The double-circuit 275 kV overhead line from Carlisle is now connected to two 120 MVA auto-transformers, and two more will be installed shortly. The firm capacity of the circuits to England is 510 MW, and the degree of interconnection is now such that it is always possible to run the most efficient generators to meet load requirements.

Reinforcement of the 11 and 6·6 kV systems by the use of 33 kV feeders has been considerable, and despite limitation of the fault duty on the 11 and 6·6 kV systems to 250 MVA, replacement of obsolete switchgear has been extensive and is still proceeding. Although many of the older circuit-breakers appear liable to be overstressed, no one has been injured by the failure of any switchgear due to inadequate breaking capacity.

On the 1st April, 1948, 186 650 consumers were supplied from d.c. systems. In that year the maximum demand on the Glasgow d.c. system was 27 MW. The work of standardization of supplies was pressed forward, so that by the end of 1957 all consumers in the South of Scotland were receiving the standard 240-volt 50 c/s supply. The difficulties of conversion facing the North of Scotland Hydro-Electric Board were more serious than those in the South, but nevertheless the number of d.c. consumers in the North was reduced from 50 000 in 1948 to 948 in 1957.

Except in isolated regions, there were few villages without electricity supply prior to 1947, but in that year only 7 000 farms, or 15% of the estimated total number of farms and crofts, had supplies. By 1957, over 37 500 farms and crofts, two out of every three in the whole country, had been connected to the Boards' systems.

The progress of the electricity supply industry in Scotland is summarized in Table 1.

Table 1

PROGRESS OF THE ELECTRICITY SUPPLY INDUSTRY IN SCOTLAND

Year	Generation		132 kV transmission		Extent of Lighting Orders		Number of consumers	Total energy sold	Maximum demand
	Number of stations	Plant capacity	Length of overhead lines	Transformer capacity	Number of burghs	Percentage of population			
		MW	miles	MW			×10^3	kWh×10^6	MW
1897	8	6·0	—	—	8	40	1·2	2·0	0·9
1907	38	79·7	—	—	43	56	33·8	64·5	43·0
1917	44	213·4	—	—	66	60	68·3	359·5	115·1
					Farms and crofts				
					Number	Percentage			
					×10^3				
1927	51	215·3	—	—	—	—	222	779·6	396·5
1937	58	895·2	600	1 000	—	—	750	1 834·6	723·5
1947	58	1 196	690	1 296	7	12	1 159	3 421·7	1 185·2
1957	171	2 400	2 222	3 320	37	66	1 661	6 791	1 950

In 1898, a labourer in Glasgow had to work for 40 minutes to earn the cost of a kilowatt-hour of electrical energy: in 1958, despite the recent rise in wage rates, he can earn the cost of a kilowatt-hour by only two minutes' work.

Electricity, which is now competitive in cost with other sources of energy for most heating requirements, may eventually become the universal source of energy for industrial, commercial and domestic purposes.

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EAST ANGLIAN SUB-CENTRE: CHAIRMAN'S ADDRESS

By R. A. W. CONNOR.

'NETWORK ANALYSERS FOR DISTRIBUTION SYSTEMS'

(ABSTRACT *of Address delivered at* CAMBRIDGE *6th October*, 1958.)

In the early days of the supply industry, when a large proportion of the load was supplied by direct current, some knowledge of Ohm's law, of the temperature rise of conductors under load, and of Kirchhoff's laws, was all that was considered essential in order to design and operate distribution systems. By the early 1920's it was apparent that the change-over from direct to alternating current was accelerating, and some knowledge of admittance methods was necessary in order to calculate voltage drops in the growing a.c. networks. At this stage the problems of short-circuit and earth-fault currents were not serious, although circuit-breakers occasionally exploded owing to the gradually increasing fault power available. Similarly, with these networks load-flow calculations were not often considered necessary even when a number of small stations were interconnected. However, with the passing of the 1926 Act and the interconnection of undertakings by the national Grid, the simple mathematics already mentioned was insufficient and it became necessary to apply vector algebra and symmetrical-component theory in order to find out the network conditions under both load and fault conditions.

With a modern interconnected network it is also necessary to estimate the growth of load with some accuracy so that networks can be designed to cater for the growth over a reasonable length of time. The operating staffs also need to know the magnitude of fault currents with both phase and earth faults so that they can select suitable protective gear and adjust and maintain it to give the best possible performance.

With complicated networks, manual calculations become very lengthy even when they are speeded up by the use of tabular methods and calculating machines operated by non-technical staff. A solution to this difficulty has been found in the use of network calculators and analysers. These comprise equipment which enables a model of the network to be made. This can then be fed with a suitable supply and various conditions on the network can be studied by the performance of the model. Fixed or 'geographic' models may be made and find some use where the networks are large and important, but universal models which can be set up to solve any problem find wider application.

The model may be supplied with either direct or alternating current. A d.c. calculator comprises an arrangement of resistors which are normally used to represent the impedances or reactances of the various circuit components. The many short-cuts that may be used with experience include: ignoring the impedance of the source, ignoring resistances and assuming that the impedance is entirely reactive, ignoring loads taken off *en route* from a feeder and ignoring the fault power of motors and synchronous machines.

The theory of symmetrical components provides a powerful tool for investigating unbalance problems, and by this means single-phase studies can be made of 3-phase systems and the currents and voltages in the various phases obtained. With calculators and analysers many problems can be solved in a comprehensive manner that would otherwise not be solved in detail owing to lack of time. The permutations in switching operations on a network may run into hundreds, but with one operator calling out the results, another can quickly record them in coloured pencils to denote different switching conditions or load growth. D.C. calculators can be used with considerable success on short-circuit problems, and when only one supply point is involved, both for load-flow and earth-fault studies. The results obtained, even though not of the highest order of accuracy, are often invaluable to both design and protection engineers.

Although much valuable work can be done on d.c. calculators, they have their limitations. Certain problems cannot be done at all with direct current and others with insufficient accuracy. An a.c. analyser gives the load flow both in P and Q, it can take account of system losses and give voltage and transformer tap positions at substations. Such knowledge is often essential. There are five or six large a.c. network analysers in this country of the impedance type operating at fixed frequencies between 500 and 1 500 c/s. A number of smaller a.c. analysers are also in course of construction which are specially suitable for distribution-system problems. These will operate at 50 c/s on the conjugate-impedance principle, in which $R' = R$, $C' = L$ and $L' = C$. In addition, the Electrical Research Association have built a large a.c. analyser which is probably unique, with a variable-frequency supply of 159–15 900 c/s. This enables variable-frequency studies to be made without using the step-by-step technique, in which all circuit-elements have to be adjusted to different values corresponding to the frequency being studied.

To obtain the maximum use from an analyser it is necessary to prepare the problem properly in advance. It is also very useful to have the operating engineer present, so that decisions can be made on the spot, and it is essential to issue a comprehensive report after each investigation to avoid later duplication of work already done.

Operating engineers, and in particular young engineers, have a right to see their system on an analyser, but they must justify this claim to analyser time by mastering the necessary mathematics and technique. It is only in this way that the full advantages can be obtained from this somewhat expensive but nevertheless invaluable equipment.

The increasing complexity of modern networks, coupled with a doubling of load every ten years, means that systems cannot be designed and operated without an ever-increasing use of calculators and analysers. The digital computer also offers exciting possibilities. The further one attempts to peer into the future the greater are the possible major changes. The digital computer then appears to offer economic advantages by the speed with which it can solve a large number of equations. It is possible, therefore, that at some future date computers may be used in distribution system planning and operation.

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RUGBY SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. M. PRICE, M.A., M.I.Mech.E., Member.

'ORGANIZING FOR TECHNICAL DEVELOPMENT'

(ABSTRACT *of Address delivered at* RUGBY *8th October*, 1958.)

Much of the work of a manager is devoted to the problem of helping others to work more successfully. The following observations on the subject of organizing for technical development are an attempt to show the extent to which management is concerned to aid the practical engineer. This survey covers the last decade and comprises hydro-electric and thermal power station practice, gas turbines, Diesel-electric installations and atomic plants, with which the author has been associated.

Extensive developments in size, efficiency and type of hydro-electric plants have been made in the face of increasingly severe competition, both from within the Commonwealth and outside. This has put a high premium on reducing weights and therefore costs of material by better design and improved manufacturing methods. In thermal power stations there has been similar rapid—almost startling—progress in respect of steam conditions and size, but ever-increasing ratings have been combined with a rapidly reducing quantity of units to be made. This year the Central Electricity Generating Board placed orders for three units, one of 550 MW and two of 275 MW, whereas ten years ago this capacity would have involved as many as 20–25 units.

Gas turbines for industrial purposes were largely a post-war development and have posed some knotty problems. Small units of 2 MW and upwards are proving their versatility in several spheres, and are especially useful in the oil industry. Sets up to 20 MW in size are also installed in this country for special duties. Although the technical development of gas turbines is fairly well known, manufacturing problems still occupy the attention of management and engineers alike. One such problem concerns the manufacture of blades and other parts to withstand extra-high temperatures.

Diesel engines have now reached the stage where radically new features are seldom found for conventional applications. With the demand for Diesel generating and pumping stations mainly coming from oversea, the emphasis is towards greater reliability as opposed to refinements in operation, and first cost is often more important than high performance. How different is this from the needs of Diesel-electric traction, where power/weight ratio and ease of control are both of great importance and new concepts of design are still possible and attractive.

The field of development in atomic power stations covers the complete gamut of physics, metallurgy, chemistry, civil engineering, mechanical engineering, heavy- and light-current electrical engineering. The problem is to pick from the many fields of possible investigation those which are most likely to be of primary importance whilst at the same time being within reasonable financial limits.

One thing is common to all the above-mentioned fields of engineering development. It is no longer possible to get along just because you can make a product: it has now to be a steadily-improving product.

How then can assistance be given to engineers to do a better job, whether in the field of development, design or manufacture? All of them are concerned with development in one form or another, and one of the duties of management is to ensure that the required tempo of development is achieved. The opportunities for action fall under three headings:

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(i) To achieve good results in technical fields, an adequate supply of good technical personnel is necessary.

(ii) Given the qualified men, the services must be provided to enable them to produce the answers.

(iii) Manufacturing facilities must do justice to the design.

Regarding the problem of securing an adequate supply of good technical personnel, it has been asserted that money is the paramount factor. This is an over-simplification. Amongst the other influences, undoubtedly a broad educational policy within the company is important. A comprehensive range of apprenticeship for all grades of personnel is necessary, with both academic and practical instruction and experience. Training is not enough: it is incumbent on management to provide good working conditions. Perhaps the most important requirement of all, however, is to ensure that work is interesting and that prospects are good and clearly seen. The current shortage of technical staff may be beneficial in forcing managements to rationalize the work of their engineers.

The second of the three criteria, namely the provision of adequate services for engineers to produce the best results, implies that engineers must have facilities under their own control to carry out their main developments. To-day one must, however, take notice of the fact that many specialized branches of science not available within conventional product departments must also be made available to the product engineer. These can cover a wide range of topics in fluid dynamics, thermodynamics, structures, mechanics, physics, metallurgy and chemistry. Then there are the services of computers, digital and analogue, and the use of other types of analogues as well. Finally, in this sector mention must be made of adequate library and reference services. These are essential for disseminating the more important information available from the mass of published material and also contained in internal reports.

Dealing now with the manufacturing services to the laboratories, central manufacturing shops, divorced from product-manufacturing shops, must be provided complete with all facilities. The accent here must be on quick service rather than minimum total man-hours per piece. Another item under this heading is one of special significance—manufacturing advice. The learning process is continuous, and from the two-way contact between designers and works stem many technical improvements in design and manufacture which in turn help to achieve the third essential, namely adequate facilities in respect of plant and buildings and supervisory services. In a company in the heavy plant field using massive equipment, it is vitally important to make a close study of plant utilization and to employ imaginative planning and adaptation in order to minimize capital requirements in what is a fast advancing field.

Finally, what of the future? The trend over the past decade has been towards a steadily increasing proportion of technical staff to production personnel, and there is every sign that this will continue for a long time. This trend towards a greater technical content of work is a good thing because it is just this high quality of technical skill in Great Britain which will enable us to keep in the forefront of developments at home and oversea and thereby to maintain and improve our living standards.

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SOUTH-WEST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By W. ADAM, B.Sc., Associate Member.

'ELECTRONIC DRIVE FOR A PAPER-MAKING MACHINE'

(ABSTRACT *of Address delivered at* GLASGOW *29th October*, 1958.)

The application of electricity to industry is a complex and fascinating subject involving specialized knowledge of various industries in order to deal effectively with their associated problems. An interesting application involved a multi-generator electronically-controlled sectional drive for a paper-making machine,* which at the time of its installation (about six years ago) was the first of its type not only in this country, but also in Europe.

In the early days all kinds of materials were used for writing and drawing, such as clay tiles, bones, skins and papyrus. Papyrus, a water reed which grows in abundance on the banks of the Nile, was used by the Egyptians for nearly 3000 years: most of the works of the great Greek and Roman scholars were written on it. The origin of paper making is somewhat obscure, but it certainly occurred in China round about A.D. 100, although it did not reach this country until the 15th century. This was hand-made paper, rags only being used as the raw material. The demand, however, increased to such an extent, particularly at the time of the Industrial Revolution, that thorough investigations were carried out to obtain additional raw materials, culminating in the use of wood, esparto grass, straw, etc.: furthermore, the mechanization of the paper-making technique was obviously essential to provide increased production.

Esparto grass is generally required for fine writing papers, such as those produced by the machine with which we are concerned. Only the cellulose content—of this or any other raw material—is useful for making paper; all extraneous matter must be removed and the grass thoroughly cleaned and purified in order to produce a quality sheet. Lantern slides were shown of the various processing stages such as the digesters, where the grass is boiled in caustic liquor; potchers, where the pulp is thoroughly washed and bleached to requirements; and beaters, where the fibres are teased out preparatory to final cleaning before passing to the paper making machine.

The consistency of the pulp, which flows in a controlled and regulated stream to the 'wire' of the machine, is of the order of 1%, i.e. 99% water and 1% fibres, and the essential problem is to get rid of the water and form a coherent sheet. Lantern slides were shown of the various sections of the machine, such as the 'wire,' an endless phosphor-bronze wire-mesh cloth which carries the pulp as it moves forward and under which are located suction boxes to remove water; the wire frame, which is hinged at one end and is given a lateral shake motion which helps to knit the fibres together; the couch roll, which drives the wire and is of the suction type to remove more water; the press rolls, which press out more water and help to form the sheet; the dryer cylinders, steam heated, which drive off the remaining moisture; the calender stacks, with steam-heated rolls, which impart the necessary polish or finish to the sheet; and the reel, on which the paper is finally wound before passing to the finishing house, where it is cut into smaller reels or sheets, according to requirements.

Including the reel, each of the 17 sections of the machine (couch roll, press rolls, dryers, etc.) is driven by a forced-ventilated compound-wound d.c. geared motor unit. The shunt-field excitation of each section motor is supplied from a common exciter, the voltage of which is held constant within very close limits by its own electronic voltage regulator. The armature of each section motor is supplied from its own d.c. generator. The entire paper-making speed range, 40–400 ft/min, is obtained by generator field control, the shunt field of each section generator being excited from its own bi-phase thyratron rectifier. The feedback principle is used for speed control of all sections: the voltage of a small d.c. pilot generator, of special design, coupled to the non-driving end of each section motor, is compared with a section reference voltage, and the difference voltage controls the output of the section-generator field thyratrons through a 2-stage amplifier and phase-shift network. Variations of section speed with fluctuations of load will vary this difference voltage, and the speed-control system will then operate to restore the section speed to the correct value.

To avoid breakage of the paper, a speed differential must exist between sections: this is termed 'draw' and is adjusted by operation of a small rheostat in the section reference-voltage circuit. The correct adjustment of 'draw' between sections is a measure of the skill and experience of the machineman and is of the utmost importance.

The reel is driven by a shunt-wound d.c. motor, the armature and field being supplied from a 6-phase half-wave and single-phase full-wave thyratron rectifier respectively. Constant peripheral speed with build-up in diameter of the reel is maintained, and tension in the paper is automatically held constant, the latter being adjustable by means of a small rheostat. Two reel motors are provided to facilitate change-over from full to empty reel.

Lantern slides were shown of the electronic cubicle-type gear, contactor panels, section controllers, master control pedestal, etc. Each section motor can be started and stopped individually from the appropriate section controller, which also houses the rheostat for 'draw' adjustment. The speed of the machine as a whole can be varied from the master control pedestal.

An adequate degree of amplification is provided so that changes of speed with load are practically negligible. The speed between sections can be held constant within $\pm 0{\cdot}1\%$, and the speed of the machine as a whole between $\pm 0{\cdot}2\%$, irrespective of load fluctuations, temperature changes and normal supply-frequency variations: these percentages are constant over the entire speed range.

* Fourdrinier machine: wire width, 122 in; speed range, 40–400 ft/min.

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SOUTH-WESTERN SUB-CENTRE: CHAIRMAN'S ADDRESS

By Captain W. W. H. ASH, R.N., Wh.Sc., A.D.C., Member.

'ELECTRICAL ENGINEERING IN H.M. DOCKYARDS'

(ABSTRACT *of Address delivered at* PLYMOUTH 16*th October*, 1958.)

The address opens with a review of the history of H.M. Dockyard, Devonport. Although Charles II, in 1677, contemplated a West Country dockyard to assist in prosecuting his war with the Dutch, it was William of Orange, as William III, who commenced operations in 1691 with the construction of a graving dock, a basin, two building slips, a ropery and certain storehouses. The site was expanded over the years up to 1789, during which three more docks and accommodation for the workmen were provided. Around 1850–60 this yard, now known as the South Yard, was substantially reconstructed and also adapted to the building of iron ships, and to-day it is concerned mainly with the building of new ships and with naval storekeeping. With the advent of steel for ships came also steam propulsion, and the additional facilities required resulted in the construction of the Steam Yard to the northward, comprising three more docks, a second basin and a magnificent engineering factory. This factory, known as the Quadrangle, although now 100 years old, continues to perform practically the same functions as when first erected. Around 1900, further expansion became necessary, and a third yard known as the Keyham Extension was added, again to the northward, to give three more large graving docks and two more fitting-out basins. This extension can be identified with the coming to the Fleet of the steam turbine, the largest battleships with heavy gun armament and electrical installations. The largest units of the Navy are fitted out here. In this yard, therefore, are to be found the turbine shop, the main electrical workshops and the radio repair facilities. Post-war developments have added further space and facilities, particularly a gunnery equipment workshop and additional electrical workshops.

A brief outline is then given of the coming of electrical engineering to the Fleet, which appears to have begun in 1870 when electric firing of guns was introduced using a pile-type battery. The dynamo first went afloat in 1875 to operate a searchlight, and general electric lighting made its appearance in 1881. This system employed distribution at 880 volts d.c. with lamps in series, and, as might have been expected, it was only the next year when the first fatal accident from electric shock on board occurred. In 1906 the supply voltage was standardized at 220, and at this time also multiple dynamo installations led to the adoption of a ring-main system of supply and distribution: an arrangement which was to remain for the next 50 years. Reference is made also to the experiments in wireless telegraphy carried out by Capt. H. B. Jackson at Devonport from 1890 onwards, and, on his recommendation, the installation of Marconi equipment in four ships in 1899. In addition to their 'high power' 220-volt systems, H.M. ships have a 'low power' system based on 24 volts d.c. to serve vital seagoing and fighting services, such as weapon-control data transmission, gun firing, navigational aids, telecommunication, etc. In latter years, however, developments in automatic control of armament, radio, aircraft servicing, etc., have required the introduction of an ever-growing number of other voltages both d.c. and a.c. (with a variety of frequencies), and now, in a large ship, some 80–90 motor-generators may be required. Increasing demands for electric power and the paramount need to reduce weight and maintenance effort resulted, in 1952, in the appearance of the first naval ship with a basic a.c. supply system and employing a 440-volt 3-phase 60 c/s distribution scheme.

The address next outlines the make-up of the dockyard organization, deals with the electrical department's structure, and states that its activities divide into three broad groups, namely shore, ships and shops with labour loadings, respectively, of around 1 000, 800 and 650: the department also bears about 500 apprentices.

The shore sections are concerned first with the dockyard electrical shore installations and secondly with a large number of Admiralty establishments external to the yard and spread through the south-western counties of England and Wales. Some details are given of the dockyard generating station (15 MW, 6·6 kV), established in 1905, and of its continuing augmentation by supplies from the South Western Electricity Board through a newly developed 33/11 kV distribution scheme. The total connected dockyard load is about 67 MW, and the present maximum demand is 23½ MW. Some of the more interesting installations are next described, such as the arrangements for giving shore supplies to ships alongside, there being provision for a total of 16 MW d.c. and planned arrangements for about 14 MVA a.c. Temporary electric lighting arrangements, using 110 volts for ships under refit, external lighting, electric cranes, capstans, welding, dock machinery and pumps, air compressors, cathodic protection and the dockyard telephone system (2 000-line p.a.b.x.) are also touched upon.

The work of the ship section is also described, this being concerned with the rewiring of defective cabling, repair of electrical machinery, domestic equipment, radio and other electronic gear, weapon-control systems, etc. Work of this type beyond the scope of the men working in the ships is removed by them to the comprehensive refitting facilities ashore, where specialists rebuild, as necessary, to full manufacturing specification standards. To convey an idea of the scope of the *matériel* handled, particulars are given of a typical ring-main distribution system in a ship with 4 000 kW of generating capacity, together with some information on ships' telecommunications, internal broadcasts, radio and the elements of the analogue computers, etc., associated with weapon-control systems.

The address concludes with a tribute to the dockyard electrical workmen employed in these shore, ship and shop activities, to whose consummate knowledge and skill so much is owed in the fitting-out and maintenance of the highly complex installations in the modern warship. Indebtedness is also acknowledged to the Lords Commissioners of the Admiralty for their kind permission to give the address, and to Mr. John M. P. Hooley, for information on the early growth of Devonport Dockyard.

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TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By L. F. ROBSON, B.A., Associate Member.

'THE FUTURE OF ELECTRICITY AND THE MAN IN THE STREET'

(ABSTRACT *of Address delivered at* MIDDLESBROUGH *1st October*, 1958.)

Past Development.—Although public electricity supply is now some 70 years old, by the time the half-way stage had been reached in 1922–23 the use of electricity for domestic and commercial supplies had really advanced very little. A distinct change came in the 1920's when supply undertakings began to be aware of the need for developing load which would not be seriously affected by slumps, and for developing load complementary to the industrial load as a means of spreading the demand curve and improving the system load factor.

About this time, serious attention began to be paid to supply economics and costing, and I may perhaps mention that the cost of supplying anyone with electricity can be divided into three components: fixed costs, which include meter reading, billing, etc., and quite a proportion of the capital charges in respect of the l.v. network; demand-related costs; and energy costs. It is important to note with regard to the demand costs that what matters is not so much the actual m.d. of the individual consumer as his contribution to the system or network m.d. The relationship between the two is broadly known as diversity—a concept which is absolutely fundamental; in fact the whole electricity supply business is founded on it.

The Present Situation.—The economic objectives of the supply industry are, first, to increase the use of electricity in all cases where the revenue is small in relation to the fixed costs, and secondly, to increase the consumption of energy in relation to the after-diversity demand; i.e. to improve the system load factor and employ plant and mains to the best effect.

From the supply industry's point of view, the important features are that consumption continues to double roughly every ten years or so; that the load factor remains rather static at just below 50%, although this is something of an achievement since the trend is for people to work shorter and shorter hours; and that, although the average consumption per domestic consumer is now about three times what it was before the war, there are still too many small consumers whose annual expenditure on electricity barely covers the fixed costs.

From the consumer's point of view, the outstanding feature is the modest increase in electricity cost relative to other fuels since the period before the war. In addition to the traditional advantages of cleanliness and convenience, electricity has now become cheaper in energy cost alone for many applications.

The Future.—It seems likely that the trend of relative costs in favour of electricity will continue, provided that the overall load factor can be maintained or improved. The important feature, of course, is the use of nuclear energy, which means lower running but higher fixed costs, and in the rest of this address I should like to consider the possibility that the man in the street may eventually take practically all his energy requirements in the form of electricity.

During the 1960's, therefore, relative to general price levels, we may expect a fall in the running component of two-part tariffs and in the final rate of block tariffs. Still more, there should be a relative fall in off-peak rates. According to Sir Christopher Hinton, the really interesting point is reached about 1970, when the nuclear generation output will approach or equal the national base load. We shall then be obliged either to switch back to the construction of coal-fired stations which can operate economically at lower load factors, or to continue to build nuclear stations with the risk at night-time of under-employing the very heavy capital investment. From a study of similar authoritative articles it seems likely that the supply industry will adopt the second alternative, and will then be in a position to sell energy at night-time at 'by-product' prices—possibly in the region of ¼d. per kWh. The man in the street will be delighted with this abundance of cheap energy, but unfortunately he may find that his premises built, say, in the 1950's are not designed to take advantage of it.

Off-Peak Thermal Storage Heating.—This appears the best means of using the cheap off-peak energy mentioned above. The principal techniques, namely floor-warming and block storage heaters, are readily applicable now for new and existing commercial premises, respectively. Floor-warming seems also very suitable for multi-storey flats and for private houses (the latter with loadings of 6–10 kW, and consumptions of 7000–15 000 kWh per annum, costing £25–50 per annum for space heating at present rates, but only perhaps £10–15 at the prospective by-product rate). Another application of thermal-storage to domestic and commercial premises is for water heating, and the storage-tank sizes required are not at all unreasonable.

Effect on L.V. Networks.—It is interesting to consider the effect of extensive thermal-storage loads on local l.v. networks. While the intention is obviously to make maximum use of existing l.v. copper, it may be that we shall have to incur heavier capital expenditure under this heading in order to improve the load factor on the generating plant. For example, housing estate l.v. networks are designed now on the basis of 2–2½ kW demand per house, but with every house equipped with off-peak space heating and water heating we may well have a total demand of about 10 kW. This figure appears formidable, but it is not really so difficult, since l.v. networks consist of a grid of distributors with substations at suitable intervals, and as loads increase the tendency will be to introduce more transforming points and only occasionally to increase the l.v. copper size. Therefore, to meet four times the present demand we may expect to spend a little more on services, l.v. mains and h.v. mains, but nearly four times as much on substations. From tentative figures it seems we might provide 10 kW per house for a capital expenditure of about £120 compared with the present £60. Each consumer might be expected to take, say, 12 000 off-peak kWh per annum, so that the cost of the heavier l.v. network would be about 0·1d. per kWh. Thus the selling price, assuming by-product prices at the bulk-supply points, would still be very favourable to the consumer.

Unmetered Supplies.—With the trend of higher fixed components and lower running components for normal supplies, it has been suggested that the time will come when we shall dispense with meters and sell electricity by the kilowatt-year, a similarity with water supplies being claimed. I do not think we shall adopt this, for the following reasons: unmetered supplies encourage waste, and wasted energy, even though it costs little to generate, means wasted plant and mains capacity; such supplies forfeit the advantages of diversity, which as previously stressed is the basis of the industry. This seems to be borne out by experience in Norway, where the tendency is to return to metered tariffs.

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NORTH-EASTERN RADIO AND MEASUREMENT GROUP: CHAIRMAN'S ADDRESS ©

By G. H. HICKLING, B.Sc., Member.

'RESEARCH FOR ELECTRIC POWER'

(ABSTRACT *of Address delivered at* NEWCASTLE UPON TYNE *20th October*, 1958.)

The address, which took the form of an informal lecture, illustrated the very wide range of research activities which are now required in a large heavy electrical engineering manufacturing organization, and showed the very varied uses which are made of electrical and electronic instrumentation, both in experimental work and as adjuncts to production processes. Although attention was mainly confined to the electrical research laboratories of a particular company, it was shown that measurements of an extremely wide range of mechanical and physical quantities are necessary in its day-to-day work.

Industrial research is necessarily related very closely to the manufactured products, which, in the organization considered, include steam and gas turbines, large generators and transformers and, in recent years, a variety of specialized plant and instrumentation for nuclear power stations. A subsidiary section of the factory also manufactures precision optical and other instruments. Although research in the nuclear engineering field has not yet attained its full impetus, this relatively new activity has, nevertheless, already greatly increased the extent and diversity of research and development work of the Department.

In the address the various types of research investigation undertaken in connection with each of the foregoing products were reviewed in turn. Researches into steam turbine problems involve vibration frequency and vibration fatigue studies on blading, both under normal test-room conditions and under simulated or actual working conditions; measurements of temperature and pressure stresses through the fixed and moving parts of the turbine; studies of bearing operating conditions and of machine vibration—all of these requiring the use of electronic measuring techniques. The development of improved methods of dynamic balancing, and the provision of 'turbine supervisory instrumentation' to ensure safe operation in service, are other instances of the application of electrical measurements in turbine engineering. For special investigations on the test-bed, or during commissioning of turbo-generator plant, both electromagnetic and capacitance-type transducers, and also resistance strain gauges, are frequently employed by the electrical research staff, to measure displacements, pressures and other quantities on both fixed and rotating parts.

Researches in connection with the development of generating plant have been equally diverse, relating to insulation problems, magnetic flux distribution, cooling, bearing behaviour and mechanical running conditions, slip-ring and commutator performance, and numerous other factors. The development of thermal unbalance on load and the occurrence of high mechanical stresses in rotor end-caps are two problems of a mechanical nature which have been extensively investigated, whilst developments in methods of cooling have led to some revolutionary advances in design. These have included, in sequence, hydrogen cooling, direct gas cooling of rotor copper, and most recently, water cooling of stator conductors. All these developments have involved extensive laboratory investigations, and in many instances new electrical measuring techniques have been required.

Transformer research work has extended over an equally wide range and has been on broadly parallel lines. The insulation problem alone may be singled out for mention here. This is primarily a question of meeting a surge test specification, which overrides the requirements for power-frequency tests. Researches involve extensive study of winding voltage stresses using the recurrent-surge oscillograph; dielectric tests on samples with microsecond surge voltages; and finally full-scale surge tests on complete transformers. In this last field, electronic techniques have recently been extensively used for measurement and recording of high-voltage transients as well as for control of the impulse test plant. Noise measurement and analysis is an important study also in connection with both machines and transformers. A new electronic instrument—the 'dispersion meter'—has been developed for checking the quality of transformer insulation during manufacture.

In work for the Optical Division, the development of highly stable electronic drives for astronomical telescopes, and of infrared spectrometers and gas analysers for the chemical industry, may be mentioned. The latter class of instrument has involved some extremely interesting electronic amplifier problems.

On the nuclear engineering side the Department's activities have been almost as diverse as those for all other production requirements. Strain measurements on unusual types of structure, pressure, temperature and flow measurements, and clearance measurements in gas bearings and seals have been undertaken. Various electro-mechanical handling and operating devices have had to be developed. The Department being responsible also for all nuclear instrumentation, many different types of electrical and electronic measuring and control devices have been investigated or specially developed in the laboratory. Reliability studies on both thermionic and transistor devices have been an important part of this work.

Another important field of activity, related to almost all of those mentioned so far, is the application of electrical simulators or computers to the solution of engineering design problems of many kinds. These include the electrolytic tank for field distribution problems; the *RC*-network thermal simulator for heat-flow studies; the analogue computer, applied to almost all complex problems of time variation; and the high-speed digital computer. All these are being used by the laboratory at the present time, a notable instance being the application of a large analogue computer to the study of safety and control problems in nuclear power plants.

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THE OBJECTIVE FOR EURATOM

By Professor F. GIORDANI.

(ABSTRACT *of a Lecture delivered before the* SUPPLY SECTION *26th March*, 1958.)

INTRODUCTION

To-day the problem of power has the same importance as that of bread towards the end of the last century. Oil and gas are making an increasing contribution in meeting world needs; serious doubts have arisen as to the possibility of producing coal in sufficient quantities to keep pace with requirements; and in Western Europe the growth of available resources does not keep pace with consumption.

These conditions justify the anxious search for new and abundant power sources competing in price with traditional ones and if possible involving reduced transportation expenses.

All our hopes are now pinned on nuclear energy. At present we can rely on fission nuclear processes and on the existing uranium and thorium reserves. We can reasonably expect to succeed in the utilization of fusion nuclear phenomena, which would make available the practically inexhaustible reserves of heavy hydrogen.

O.E.E.C. INVESTIGATION

Studies of the supply of and demand for power in the various countries were discussed at the First International Conference on the Peaceful Uses of Atomic Energy in Geneva, August, 1955. In May, 1955, the Secretary-General of O.E.E.C., who had been collecting information and making proposals for close co-operation in this field, submitted to the Council of Ministers a report on European power problems. As a result a commission of eight was set up, known as the Hartley Commission, entrusted with the task of collecting more data on power requirements and resources of member countries, together with related economic problems. They were also to make proposals to pave the way to a solution within the framework of European co-operation.

Table 1

ENERGY BALANCE OF O.E.E.C. COUNTRIES

	1955 Base year	1960	1975
Consumption			
Maximum		860 (118)	1 300 (178)
Mean (taken as most probable)	730 (100)	840 (115)	1 200 (165)
Minimum		820 (112)	1 100 (151)
Probable indigenous output	584	645	755
Probable import ..	146	195	445
Import as percentage of primary consumption	20%	23%	37%

Figures are given in million metric tons hard coal equivalent (m.t.e.c.). (Index figures in brackets 1955 = 100.)

The report was published in May, 1956. The data start from 1955, when the 17 member countries consumed 730 million equivalent tons of coal (m.t.e.c.), 20% imported and only 80% home-produced. The development of consumption is predicted over 20 years, up to 1975 (see Table 1), and the mean consumption is considered the most probable value.

The mean estimate of the Hartley Commission corresponds to an annual increase of 2·5%, while the maximum estimate gives 2·9%, which figure has already been exceeded during the last two years. These are the most debated figures and merit further consideration.

WORLD TRENDS

Table 2 gives data for world power production from 1870 to 1955. During that period the average rate of annual increase was 3·28%. From 1870 to 1900 it was 4·33%, rising to 4·58% between 1900 and 1913. Between 1913 and 1955, a period covering two world wars and the 1930–31 crisis, the average annual rate fell to 2·13%. Assuming normal development, 4% for the 85 years from 1870 to 1955 would not be far from the truth.

Table 2

WORLD PRODUCTION OF COMMERCIAL ENERGY

	Hard coal	Brown coal	Oil	Natural gas	Hydro-electric power	Total
	m.t.e.c.	m.t.e.c.	m.t.e.c.	m.t.e.c.	m.t.e.c.	m.t.e.c.
1870	203	4	11	—	—	218
1900	701	22	29	9	16	777
1913	1 216	39	77	22	45	1 399
1955	1 604	152	1 086	360	190	3 392
	Percentage of World Production					
1870	93	2	5	—	—	100
1900	90	3	4	1	2	100
1913	87	3	5	2	3	100
1955	47	4	32	11	6	100

(i) Primary energy in so far as it is commercially used, wood and waste fuels are excluded.

(ii) Production is measured in million metric tons hard coal equivalent (m.t.e.c.). 1 metric ton = 0·984 ton.

(iii) Conversion factors:

Hard coal	7 000 kcal/kg	12 600 B.Th.U./lb
Brown coal	2 100 kcal/kg	3 780 B.Th.U./lb
Oil	10 000 kcal/kg	18 000 B.Th.U./lb
Natural gas	9 000 kcal/m³	1 010 B.Th.U./ft³
Hydro power: 1870–1913	7 000 kcal/kWh	27 800 B.Th.U./kWh
1955	2 800 kcal/kWh	11 100 B.Th.U./kWh

From these and other considerations it is felt that the consumption estimates of the Hartley Commission were too cautious.

So far as supplies were concerned, the Hartley Commission considered that in 1975 only 80 m.t.e.c. of the 1 200 m.t.e.c. required by O.E.E.C. countries would be supplied from nuclear fuels. When their report was published it was widely thought that the necessary imports till 1975 could be provided by oil and oil products. Some experts had misgivings. They had in mind the heavy investments required by the oil industry, the possible changes in coal price policy if coal-mining continued to decline, the necessity for paying for the majority of oil imports

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through hard currencies and, finally, the dependence for oil supplies on a limited region of the politically unsettled Middle East. At the end of 1955 the ascertained oil reserves of the free world amounted to 24 billion tons, of which only 17% were located in the United States and 83% in the rest of the world. About four-fifths of the latter fraction belonged to the Middle East.

Very soon after the publication of the Hartley report, anxiety about the regularity of supply was dramatically confirmed by the Suez Canal crisis, in the middle of 1956, which proved a very serious threat to world peace.

EURATOM INVESTIGATION

These circumstances enhanced the interest shown in the initiative taken by the Foreign Ministers of the countries participating in the Messina Conference of the European Coal and Steel Community, which aimed at the establishment of a joint agency for the closest co-operation in the field of the peaceful uses of atomic energy. As a result of this conference, in November, 1956, a committee of three experts was asked to compile a report on the amount of nuclear energy which could be produced in the near future in the six countries and the means to be employed for this purpose. Although a definite programme was difficult to establish, a target had to be indicated which might serve as a basis for such a programme.

The experts submitted their report in May, 1957, shortly after the conclusion of the treaty for Euratom, which was signed in Rome on the 25th March, 1957. Their study was founded on the law of the increase in power demand as a function of time, and to this end the investigations already under way at the High Authority were utilized even before their publication. Increase in power demand and increase of the gross national production (g.n.p.) are correlated through suitable correlation coefficients, varying from country to country and also from one period under consideration to another. According to the prospects and conditions of general economic development in the Community's countries, an annual rate of increase of gross national product of 4·3% was assumed during the first 10 years and of 3·1% during the following 10 years. Due account was also taken of the increase in population which is assumed to be fully employed, of a possible further decrease in the number of hours worked per year, and of a substantial increase in productivity. The results obtained for the total energy requirements are scheduled in Table 3.

Taking the total requirements of the six countries in 1955 as 100, we obtain an index of 183 for 1975. This is to be compared with the two figures of 165 and 178 which correspond, respectively, to the mean and the maximum forecasts of the O.E.E.C. Committee.

The index 183 involves an average annual rate of increase equal to 3·1%, which seems to be more than justified, as compared with the value deduced from the historical trend of world consumption, which, as suggested above, might be fixed at around 4%.

The gradually increasing production of primary energy in the Euratom countries was evaluated by a mixed committee entrusted with the task of studying the structure and trends of their energy economy. They formulated an optimistic estimate and a conservative one, between which they located the evaluation of probable domestic production, which was utilized for further calculations. The difference between the two limiting evaluations depends essentially on the estimated amount of coal mined, for which the following assumptions were made:

(*a*) That 30 new pits will start operating.
(*b*) That the output per man and per shift may gradually increase by 30% during the 20 years.

Table 3

TOTAL ENERGY REQUIREMENTS OF THE EURATOM COUNTRIES

	German Federal Republic*	Belgium	France	Italy	Luxem-bourg	Nether-lands	Six countries
Gross national production							
1955–65 (1955 = 100)	155	139	149	163	115	138	152
1965–75 (1965 = 100)	137·5	127	134	142·5	110·6	126·5	135·5
Ratio of changes in energy requirements to changes in g.n.p.							
1955–65	0·70	0·70	0·90	1·00	0·95	0·90	0·79
1965–75	0·70	0·75	0·95	1·05	0·95	1·00	0·83
Energy requirement index							
1955–65 (1955 = 100)	138·5	127·3	144·1	163·0	114·2	134·2	141·3
1965–75 (1965 = 100)	126·2	120·2	132·2	144·6	110·1	126·5	129·8
Energy requirements†‡ (Estimated apparent consumption, m.t.e.c.)							
1955	182	34	107	47	4	27	400
1960	214	38	129	59	4	31	475
1965	252	43	154	76	5	36	566
1970	286	47	178	92	5	40	648
1975	318	51	202	110	5	45	731

* Since the 1st January, 1957, the Saar Territory belongs to the Federal Republic; 1955 figures for the Saar have been added to the figures of the Federal Republic.
† The figures in the above Table are slightly different from the data contained in the Mixed Committee's report. Apart from revisions subsequently supplied by individual countries, the differences are due to the fact that in this calculation the production of hydro-electric power over the whole period has been computed on the basis of an equivalence of 400 grammes hard-coal equivalent per kWh. This corresponds to the specific fuel consumption prevalent in 1956 in modern thermal power stations.
‡ Figures for 1960 and 1970 are interpolated.

Table 4

PRODUCTION OF PRIMARY ENERGY IN THE EURATOM COUNTRIES (m.t.e.c.)

	1955	1960	1965	1970	1975
Optimistic estimate					
Hard coal	243·3	262	285	300	320
Brown coal	28·5	32	40	45	49
Oil	7·5	24	40	55	71
Natural gas	5·5				
Hydro-electricity ..	30·9	35	45	50	56
Total	315·7	353	410	450	496
Conservative estimate					
Hard coal	243·3	245	250	262	277
Brown coal	28·5	32	40	45	49
Oil	7·5	23	34	36	43
Natural gas	5·5				
Hydro-electricity ..	30·9	35	45	50	56
Total	315·7	335	369	393	425
Estimate of probable indigenous production					
Hard coal	243·3	254	265	279	293
Brown coal	28·5	32	40	45	49
Oil	7·5	13	19	24	29
Natural gas	5·5	10	15	18	22
Hydro-electricity ..	30·9	35	45	50	56
Total	315·7	344	384	416	449

The optimistic estimate assumes that, in spite of the tendency to reduce the working week and to lengthen annual holidays, the number of production days per year will not go below 300. The conservative estimate assumes that the trend of future production will be reflected in a reduction to 260 working days per year.

It has been assumed that the maximum possible use will be made of all existing deposits of lignite, the extra production being used as fuel in power plants. For hydro-electric resources the highest possible exploitation has been assumed.

One of our greatest doubts concerned indigenous output of oil and natural gas, and we have therefore simply accepted the predictions of individual countries. The contribution of the oil deposits recently discovered in the Sahara is estimated at 10 m.t.e.c. in 1960 and 40 m.t.e.c. in 1965, but this was included in the imports of the six countries.

All the data collected are shown in Table 4, and those corresponding to the estimated probable indigenous production are used in order to calculate, by difference, the probable tendency of imports (see Table 5).

Table 5

PROBABLE TREND OF NET IMPORTS

	1955	1960	1965	1970	1975
Estimated consumption, m.t.e.c.	400	475	566	648	731
Indigenous production, m.t.e.c.	316	344	384	416	449
Net imports, m.t.e.c. ..	84	131	182	232	282
Net imports, % ..	21·0	27·5	32·2	35·9	38·6

Imports reached 84 m.t.e.c. in 1955 and would increase to 282 m.t.e.c. in 1975, which means that they would increase from 21% of the estimated total consumption to 38·6% at the end of the 20 years. In the Hartley report, they would increase from 20% to 37% on the basis of the mean estimate of consumption for the 17 member countries of the O.E.E.C.

The experts of Euratom have been concerned about the tremendous financial charge which such imports would involve and about the very heavy pressure that they would put on the balance of foreign trade of the six member countries. It would be difficult indeed to admit that their exports could increase by 235% during the 20 years under consideration, i.e. that they could reach the same expected percentage increase of power imports, assuming no rise in prices.

PROPOSED EURATOM NUCLEAR DEVELOPMENTS

A target was urgently needed that could bring the maximum improvement in the situation and could be attained through a programme to be started as soon as possible in the six countries.

The possibility of a rapid start was supported by the favourable results of British experience after the successful operation of the Calder Hall plants since October, 1956. Such unquestionable success had induced the British Government to formulate a new programme in addition to that outlined by the White Paper, so as to bring installed nuclear power to 5–6 million kW by 1965. This programme had started in 1955, whereas a programme of the six Euratom countries, apart from some minor French achievements already under way, could not start before the end of 1958.

Experience teaches that the erection of a big nuclear plant takes about four years, and therefore the first appreciable output in the Community's countries might be expected only in 1963. A reasonable target could be fixed with the aim of holding imports at the level they would have reached at that date, i.e. at 165 m.t.e.c., according to the above forecasts (see Fig. 1).

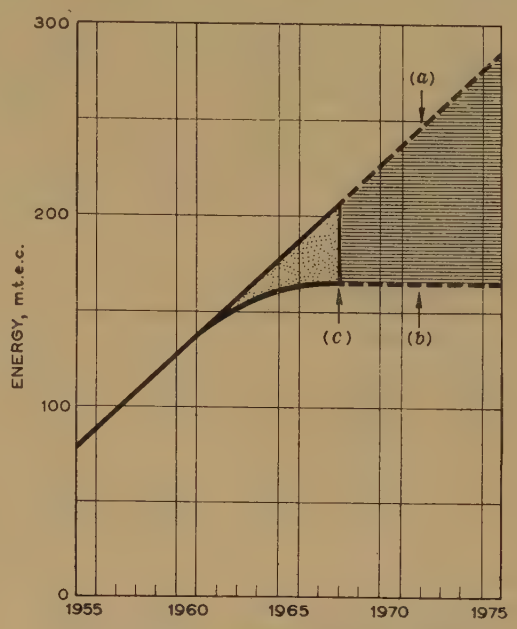


Fig. 1.—Energy imports of the six countries.
(*a*) Net imports without nuclear power.
(*b*) Net imports with nuclear power.
(*c*) Nuclear target of 15 million kW.

The only immediate possible application of nuclear energy is limited to the production of electricity in big power stations, and it was therefore a question of estimating whether the proposed amount of production could be disposed of in this field.

Table 6 gives an analysis of the requirement data into specific and non-specific parts. Electrical power, as a secondary

Table 6

TYPES OF ENERGY REQUIRED FOR SPECIFIC CONSUMER NEEDS

	1955		1965		1975	
	m.t.e.c.	%	m.t.e.c.	%	m.t.e.c.	%
Specific requirements:						
Electricity	92	23·0	161	28·5	253	34·5
Hard coal	114	28·4	144	25·4	168	23·0
Oil	21	5·3	41	7·2	63	8·6
Non-specific requirements	173	43·3	220	38·9	247	33·9
Total requirements	400	100·0	566	100·0	731	100·0

form of power, represents a specific requirement for the Euratom countries; but over half of it is produced by 'other thermal' stations, i.e. other than hydro, lignite or blast-furnace gas stations, the primary energy consumption of which is non-specific, and in this section nuclear power stations can find their place.

Table 7 includes the data on the net capacity and net annual output pertaining to different types of power stations. The distribution is made in accordance with information supplied by competent authories in individual countries. Nuclear outputs could be used only for the last group, namely other types

Table 7

NET CAPACITY AND NET ANNUAL OUTPUT OF DIFFERENT TYPES OF POWER STATIONS

	1955	1960	1965	1970	1975
Net capacity, electrical MW:					
Hydro-electric	19443	23800	30040	36030	43230
Blast furnace gas	1514	1850	2130	2450	2800
Lignite	3678	5000	7500	9700	12000
Other thermal*	26251	37900	52800	73400	96500
Total	50886	68550	92470	121580	154530
Net output, TWh/year:					
Hydro-electric	73	86	107	124	139
Blast furnace gas	8	9	11	13	15
Lignite	20	30	45	58	72
Other thermal*	90	141	208	302	410
Total	191	266	371	497	636
Fuel consumption, m.t.e.c. year:					
Other thermal	48	70	93	130	164

* This item includes pit-head power plants and co-operative stations of the mining industry which are based on low-grade coal. At the end of 1955 their net capacity amounted to 4970 electrical MW and their output 25 TWh.

of thermal plants, requiring a fuel consumption of 48 m.t.e.c. in 1955, which is bound to increase to 164 m.t.e.c. in 1975.

Further details of capacities, outputs, load factors and fuel consumption of such plants, are given in Table 8 for 1960–67.

Fig. 2 shows the capacities of thermal electricity plants which should start operating every year. A distinction is made between the replacements of old plants and effective new capacities. The shaded area corresponds to the place which nuclear plants might be given up to 1967 for a total capacity of 15 million kW. By then, as shown by Table 9, the total power imports should reach

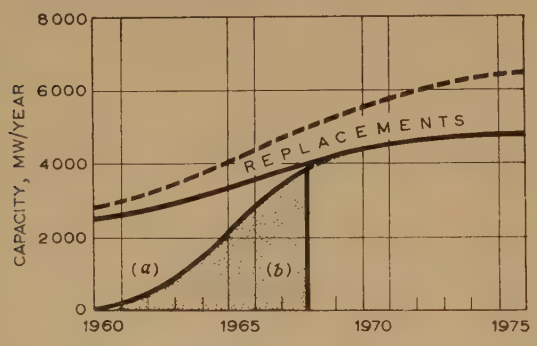


Fig. 2.—Capacity of thermal electricity plant brought into service each year.

207 m.t.e.c.; the installation of nuclear plants would release 43 m.t.e.c. of conventional fuels and 61 m.t.e.c. would still be required as coal or fuel oil.

According to the expectations of the Hartley report, the 16 member countries of O.E.E.C., except Great Britain, should have erected by the end of 1975 nuclear plants involving the release of 40 m.t.e.c. as conventional fuels.

The target of Euratom is to achieve these results eight years earlier through the efforts of the Euratom countries alone. The target is an ambitious one, but it is justified remembering that since the publication of the O.E.E.C. report the British programme of the White Paper has been increased threefold, from 2 to 6 million kW of power installed.

Table 8

PREDICTIONS OF CAPACITY AND OUTPUT 1960–67

End of year	Capacity equivalent	Load-factor	Output	Fuel consumption	
	MW	hours/year	TWh/year	g/kWh	m.t.e.c./year
1960	37900	3720	141	500	70
1961	40550	3775	153	490	75
1962	43300	3820	166	480	80
1963	46250	3865	179	470	84
1964	49400	3905	193	460	88
1965	52800	3940	208	450	94
1966	56500	3980	225	440	99
1967	60450	4015	243	430	104

Table 9

NET IMPORTS AND FUEL CONSUMPTION

	End of 1960	End of 1965	End of 1967
	m.t.e.c./year		
Net energy imports of six countries:			
Without nuclear power	136	187	207
With nuclear power	136	164	164
Fuel released by nuclear plant ..	0	23	43
Fuel burnt in conventional plants ..	70	70	61

COMPARISON WITH BRITISH PROGRAMME

The Euratom target for 1967 is two and a half times as high as the British one, while the ratio of population is 3 : 1 and that of electricity output is 2·8 : 1.

The six countries are starting from a far less favourable position than Great Britain in the matter of needed imports (23% instead of 12%).

In order to judge the feasibility of the programme demanded

by the proposed target, we had to consider some further possibilities, namely:

(*a*) Securing a supply of nuclear fuel to the amount required.
(*b*) Erecting the new plants within the expected time and without an excessive disbursement of hard currency, which might cancel the expected improvement in the balance of payments.
(*c*) Feeding into the existing network the large amounts of nuclear energy, which are to be produced with a high load factor, for economic reasons.

All these points have been examined carefully, as far as possible, by the committee of experts.

Our exchanges of views with the Canadian, British and American authorities proved that the availability of nuclear fuels is not to be considered as a limiting factor. This was clearly stated in the Joint Communiqué issued on the 8th February, 1957, by the Department of State, the President of the Atomic Energy Commission of the United States, and the Euratom Committee. The further developments in the establishment of the International Atomic Energy Agency (I.A.E.A.) under the control of the United Nations, as well as the agreements under way in favour of Euratom, may be considered as evidence of an excellent spirit of co-operation promoted with generous assistance from the most advanced countries. This represents the best guarantee that the target fixed for Euratom will be attained, while waiting for the day when nuclear fuels may be regularly on the market.

The benefits connected with the replacement of traditional by nuclear fuels would be annulled if we had to purchase abroad the plant we require for the accomplishment of our programme.

At present, and for years to come, the capital cost of nuclear plants approaches that of hydro-electric power stations, and therefore, should we have to ensure the service of interests and amortizations through foreign currency, the balance of payments would by no means be improved and we might even run the risk of making our position worse.

We therefore had to make sure about the possibility of carrying out most of our construction within the territories of the Community while depending on foreign supplies only for small amounts.

The investigations show that, by taking suitable and timely steps, the 'content of importation' may be limited initially to about 50% and reduced to a very low level within the following years, when the annual volume of construction would be gradually increasing. Foreign currency involved in the planned investments would be about 20%, as an average for the 10-year period under consideration.

The capacities of the existing national industries involved in the programme seem to be sufficient on the basis of the following comparative estimate.

The British industries have stated that within the next 10 years they would be in a position to supply the 6 million kW for the national expanded programme, and, furthermore, that they might export all the machinery required for an equal amount of power. This means a total producing capacity of about 12 million kW, in 10 years.

According to an investigation which the O.E.E.C. carried out in Western Europe, the mechanical and electrotechnical industries of the six Euratom countries have a total capacity exceeding by 60% that of the corresponding British industries. Therefore, through an effort similar to that of Great Britain, our national industries could supply within 10 years the equipment needed for nuclear power stations producing a total of 16 million kW.

This is a rough estimate which ought to be improved and integrated to determine the steps to be taken in due time to enable our industries to produce even the most specialized components, e.g. pressure shells, or special materials such as nuclear-grade graphite; but these problems will not raise insurmountable difficulties.

The production and reprocessing of nuclear fuels will be the next step, and this is a field where the best results can be achieved through the closest co-operation between member countries, which will have to create common plants and thus reach the lowest possible costs.

We discussed at length the possibility of economically feeding the power we could obtain into the existing networks. Nuclear plants, characterized by a high capital cost and a low operating cost, will be economical only when they can operate at a high load factor. All economic estimates attempted so far are based on the assumption that this factor may reach 80%, corresponding to 7 000 hours of operation per year. According to this assumption, the output of electrical power from the 15 million kW of nuclear power installed in 1967 would amount to 25% of the total requirements by that time. The British programme would lead to the production by nuclear systems of 30% of the total requirements by 1965. In neither case can we hide the difficulties which may arise before such high percentages can find their place as base loads in the so-called monotonous diagram of total loads.

The preliminary study promises well for the feasibility of the programme, but further investigations are needed to establish the most satisfactory breakdown into successive steps and to find the best way of handling the energy. Some supplementary recourse to storage, with the extension of the practice of pumping and the construction of small reservoirs to meet daily peak-loads, will be needed.

CONCLUSION

The Euratom committee attempted to go deeper into the study of costs by taking advantage of all available data and all additional information which were largely supplied by the authorities and manufacturers of the United States, Great Britain and Canada. We may conclude, on this basis, that nuclear energy is about to become competitive with traditional energy, when considering the marginal production through imported fuels. To supplement the available data and to clarify some points which are still obscure, we fixed the end of 1958 as a reasonable term for final decisions about the plants to be erected first.

As regards Italy, an agreement has been reached between the International Bank for Reconstruction and Development and the Italian Government with a view to collating the offers of the manufacturers and evaluating them critically, in order to reach the most reasonable decisions on the choice to be made. The U.K.A.E.A., the U.S.A.E.C. and Atomic Energy of Canada, Ltd., offered their widest assistance for this study.

An extraordinary spirit of co-operation is growing in all countries of the free world, aiming at a more rapid application of nuclear energy for pacific uses.

Such a spirit of co-operation calls for all our admiration and gratitude, and we feel sure that it will set an example for the way we have to follow to achieve our peaceful aims in every field of human activity.

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A NEW METHOD OF DETERMINING ROTOR LEAKAGE REACTANCE AND RESISTANCE OF A THREE-PHASE INDUCTION MOTOR

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SUMMARY

The paper develops a new method of determining the rotor leakage reactance and resistance of a 3-phase induction motor. Stationary flux distribution of constant magnitude is produced in the air-gap of the machine by supplying direct current to the stator windings. The rotor is driven at various slip speeds simulating the conditions of a 3-phase induction motor. The power input to the rotor is measured. The flux distribution in the stator teeth per pole pitch is measured by use of search coils and a ballistic galvanometer when d.c. excitation to all three phases of the stator is suddenly removed. The voltage induced per phase in the stator due to this change of flux linkage is calculated. An expression is developed for rotor leakage reactance and resistance.

The theory is proved by experimental work. The performance is calculated using the rotor constants measured by this method and is compared with that obtained by no-load and locked-rotor tests and by an actual load test. A comparison of results justifies the determination of rotor constants by this new method.

LIST OF SYMBOLS

b = Susceptance.
B = Flux density.
C_n = Maximum value of nth harmonic.
V_{ph} = Phase voltage.
g = Conductance.
I_{dca}, I_{dcb}, I_{dcc} = Equivalent direct currents for phases a, b and c.
I_0 = R.M.S. value of the no-load phase current.
$I_{0n\,max}$ = Maximum value of the nth harmonic of the no-load phase current.
1 = Length of conductor.
m_1 = Number of stator phases.
n = Rotor speed, r.p.m.
n_s = Synchronous speed, r.p.m.
P = Rotor input, watts.
r_2' = Rotor resistance per phase referred to stator.
s = Fractional slip.
v = Velocity of conductor.
x_2' = Rotor standstill leakage reactance referred to stator.
α_n = Angle of lag of the nth harmonic with respect to the fundamental.

(1) INTRODUCTION

The general method of obtaining the performance characteristics of a polyphase induction motor is to perform a load test. Otherwise, the standard method is to determine the equivalent circuit from the no-load and locked-rotor tests on the motor and then to calculate the performance. For an accurate determination of the equivalent circuit, it is necessary to determine accurately the stator and rotor constants referred to the stator. The no-load test gives the core, windage and friction losses, while the locked-rotor test gives the total impedance of the induction motor. This is separated into the total leakage reactance and total resistance. In the case of a slip-ring machine, the total resistance obtained from the locked-rotor test is divided into stator resistance and rotor resistance in the ratio of their respective d.c. resistances. In the case of a squirrel-cage machine, the stator a.c. resistance is obtained by multiplying the d.c. resistance by a factor which varies from 1·2 to 1·6 to allow for skin effect. The rotor resistance is obtained by subtracting this stator resistance from the total resistance. In the case of total leakage reactance, the division is made half to the stator and half to the rotor; alternatively it is divided in the ratio of their respective resistances. The paper develops a more accurate method of dividing the equivalent leakage reactance and resistance.

(2) PRINCIPLE OF MEASUREMENT OF ROTOR LEAKAGE REACTANCE AND RESISTANCE

The method is based on the measurement of power input to the rotor when driven in a stationary flux of the same magnitude as the rotating flux, thus simulating the conditions of running of an induction motor, and on the measurement of flux per pole in the air-gap by the use of a search coil under each tooth.

(2.1) Production of Stationary Flux Distribution in Air-Gap

The stationary flux distribution in the air-gap is obtained by connecting two of the stator terminals together and connecting these and the other stator terminal across a d.c. supply. A direct current $I_{dc} = (\sqrt{2})I_0$ is supplied when the stator is connected in star, and $I_{dc} = 1{\cdot}5(\sqrt{2})I_0$ when the stator is delta connected, where I_0 is the no-load phase current. If the waveshape of the current is purely sinusoidal, this will give the correct stationary flux distribution to simulate the a.c. condition when the instantaneous current in one phase is a maximum and the currents in the two other phases are negative half-maximum.

If the waveshape of the no-load phase current with a.c. operation is not sinusoidal, the waveshape of the phase current is obtained and the various harmonics are calculated. The equivalent direct current is calculated for each harmonic, and the total equivalent direct current is calculated. The effective direct current required in each phase to produce the same flux distribution will be:

$$I_{dca} = C_1 + C_3 \cos \alpha_3 + C_5 \cos \alpha_5 + \ldots + C_n \cos \alpha_n + \ldots \quad \ldots\ldots (1)$$

$$I_{dcb} = \left[C_1 \cos \frac{2\pi}{3} + C_7 \cos \left(\frac{2\pi}{3} + \alpha_7 \right) + C_{13} \cos \left(\frac{2\pi}{3} + \alpha_{13} \right) + \ldots \right] + \left[C_5 \cos \left(\frac{4\pi}{3} + \alpha_5 \right) + C_{11} \cos \left(\frac{4\pi}{3} + \alpha_{11} \right) + \ldots \right] + (C_3 \cos \alpha_3 + C_9 \cos \alpha_9 + C_{15} \cos \alpha_{15} + \ldots) \quad . \quad (2)$$

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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$$I_{dcc} = \left[C_1 \cos\frac{4\pi}{3} + C_7 \cos\left(\frac{4\pi}{3} + \alpha_7\right) + C_{13} \cos\left(\frac{4\pi}{3} + \alpha_{13}\right) + \ldots\right] + \left[C_5 \cos\left(\frac{2\pi}{3} + \alpha_5\right) + C_{11} \cos\left(\frac{2\pi}{3} + \alpha_{11}\right) + \ldots\right] + (C_3 \cos\alpha_3 + C_9 \cos\alpha_9 + C_{15} \cos\alpha_{15} + \ldots) \quad . \quad (3)$$

These equations are derived in Appendix 10.1.

(2.2) Simulation of Conditions of Running as an Induction Motor

If the rotor is stationary, there is no relative motion between the rotor conductors and the stationary air-gap flux produced as described in Section 2.1. Therefore a stationary rotor with a stationary flux distribution of constant magnitude in the air-gap corresponds to a synchronously-running rotor with synchronously-rotating flux of constant magnitude, and a rotor driven in the stationary flux by an external motor at a speed n is equivalent to a rotor running at slip s with a rotating flux of the same magnitude, where

$$s = n/n_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The main difference between normal operation and this method is that here no torque which can be used as a mechanical output is developed in the rotor.

To simulate the actual conditions, the magnitude and waveshape of the alternating current taken by the motor under normal operation with a slip s must be known. From this the equivalent d.c. excitation can be calculated and the stator phases supplied with the appropriate currents.

(2.3) Measurement of Flux per Pole

A search coil is introduced at the root of each tooth, the ends of the coils are connected in turn to a ballistic galvanometer, and d.c. excitation to the three phases is suddenly removed. The ballistic galvanometer having been calibrated with the help of the Hibbert magnetic standard, the magnitude of the change of flux linkages, and hence the change in flux, can be calculated. Neglecting the residual flux in the teeth, this will be the flux existing in the teeth with d.c. excitation on. The flux in all the teeth is measured in this way. Then assuming that the flux is uniformly distributed in each tooth, and neglecting the flux passing through the bottom of the slot, the distribution at the root of the teeth can be obtained. This will be the same as the air-gap flux distribution, if the slot leakage is neglected. From this distribution, the voltage induced in the stator per phase can be calculated.

(2.4) Theory of the New Method

The stator is supplied with equivalent direct currents, and by rotating the rotor at a speed $n = sn_s$, the working conditions at slip s are simulated. Knowing the losses in the driving motor and the friction and windage loss of the induction motor at speed n, the input to the induction-motor rotor is calculated.

The input power to the rotor is made up of the rotor I^2R loss and the rotor hysteresis and eddy-current losses. In the normal operation of induction motors, the slip is low (less than 10%) and at the slip frequency iron losses can be neglected.

The rotor I^2R losses, P_1 at a speed corresponding to slip s_1, and P_2 at a speed corresponding to slip s_2, are related as follows:

$$\frac{P_1}{P_2} = \left(\frac{s_1}{s_2}\right)^2 \frac{(r_2'^2 + s_2^2 x_2'^2)}{(r_2'^2 + s_1^2 x_2'^2)} \quad . \quad . \quad . \quad . \quad (5)$$

$$a^2 = \frac{s_2^2 P_1 (s_1^2 - s_2^2)}{(s_1^2 P_2 - s_2^2 P_1)} - s_2^2 \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $$a = \frac{r_2'}{x_2'} = \frac{r_2}{x_2}$$

$$P_1 = \frac{m_1 s_1^2 V_1^2 a x_2'}{a^2 x_2'^2 + s_1^2 x_2'^2} = \frac{m_1 a s_1^2 V_1^2}{x_2'^2 (a^2 + s_1^2)} \quad . \quad . \quad . \quad (7)$$

$$x_2' = b' V_1^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where $$b' = \frac{m_1 a_1 s_1^2}{P_1 (a^2 + s_1^2)} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The voltage induced in the stator per phase, V_1, can be calculated knowing the flux distribution per pole, and the value of r_2' and x_2' can then be calculated.

(3) DETAILS OF INDUCTION MOTOR

The machine is a 230-volt 3-phase squirrel-cage induction motor, normally delta connected, and designed to develop 3h.p. as a 4-pole machine with an efficiency of 80% and a power factor of 85%. All 36 coils in the stator are brought out to a terminal board. Search coils (5 turns of No. 25 s.w.g.) are introduced at the root of each tooth, and their terminals are brought out to a separate board. A d.c. motor with dynamometer (220 volts, 10h.p., 1500r.p.m., compound wound) was used to drive the rotor of the induction motor.

(4) TESTS AND CALCULATIONS

The following tests and calculations were carried out:

(*a*) Core and windage loss of the d.c. machine for the various speeds and excitations.

(*b*) Friction and windage loss of the induction motor at various speeds.

(*c*) Variable-voltage test (no-load) on the induction motor.

(*d*) Locked-rotor test on the induction motor.

(*e*) Measurement of stator resistance per phase of the induction motor.

(*f*) Load test on the induction motor. The load was adjusted by varying the excitation of the d.c. machine so that it worked as a generator connected back to the d.c. mains.

(*g*) Determination of the waveshape of the phase current of the induction motor at various speeds.

(*h*) Harmonic analysis of the wave. The 12-ordinate method was used for the analysis.

(*i*) Determination of equivalent excitation: Using eqns. (1), (2) and (3), for 1450r.p.m. or 3·3% slip, the equivalent d.c. excitations are: $I_{dca} = 2{\cdot}91$amp; $I_{dcb} = -1{\cdot}379$amp; $I_{dcc} = -1{\cdot}378$amp. For 1400r.p.m. or 6·67% slip, the equivalent d.c. excitations are: $I_{dca} = 4{\cdot}0175$amp; $I_{dcb} = -1{\cdot}88$amp; $I_{dcc} = -2{\cdot}08$amp.

(*j*) Calibration of ballistic galvanometer with a Hibbert magnetic standard.

(*k*) Determination of rotor input and flux distribution by the new method:

The direct currents flowing through phases *a*, *b* and *c* of the stator of the induction motor are adjusted to the values I_{dca}, I_{dcb} and I_{dcc} calculated for the slip. The speed of the d.c. machine running as a motor is adjusted to the required slip speed. Using the ballistic galvanometer connected to all the search coils in turn, the complete flux distribution is obtained. The experiment is repeated for various slips. The rotor input is measured at different slips. At $s_1 = 0{\cdot}0667$, $P_1 = 91{\cdot}40$ watts; at $s_2 = 0{\cdot}0333$, $P_2 = 22{\cdot}85$ watts.

(*l*) Determination of voltage induced per phase in the stator: The ballistic galvanometer throws obtained in (*k*) are expressed in webers. Assuming that the flux is distributed uniformly in each tooth, and knowing the length of each tooth, the flux per unit length of the tooth, and hence the flux distribution over the pole pitch is determined. The flux will be rotating at synchronous speed when the motor is working normally on a.c. mains.

Using the relation, $e = Blv$, the voltage induced in a conductor cutting the flux at a velocity corresponding to the synchronous speed is calculated. Considering the distribution of the winding, the voltage induced in one coil, in a coil group, and in each phase is calculated. V_{ph}^2 is plotted and its r.m.s. value is calculated. This turned out to be 213 volts.

(*m*) Determination of r_2' and x_2':

Knowing the values of P_1 and P_2 at slips s_1 and s_2, from eqn. (6) the value of a was obtained as 0·943. From eqn. (9), $b' = 1{\cdot}542 \times 10^{-4}$. From eqn. (8),

$$x_2' = b'V_1^2 = 1{\cdot}542 \times 10^{-4} \times 213^2 = 7 \text{ ohms}$$

and

$$r_2' = ax_2' = 0{\cdot}943 \times 7{\cdot}00 = 6{\cdot}6 \text{ ohms}$$

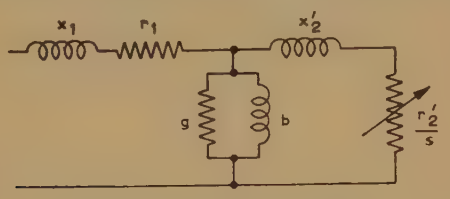
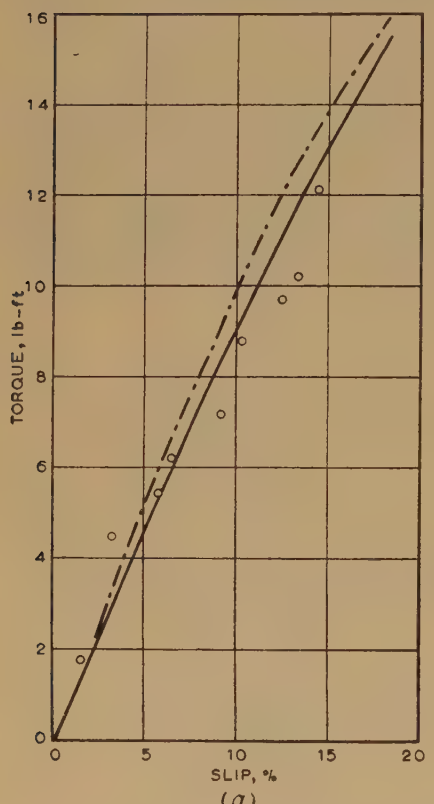
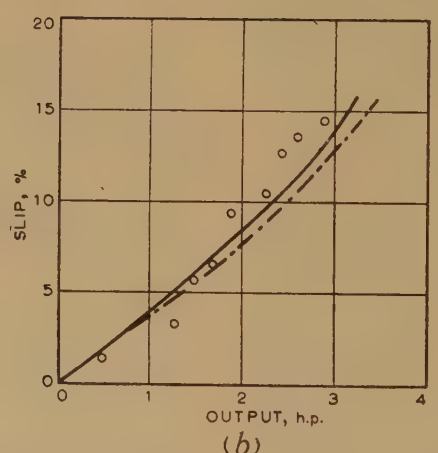
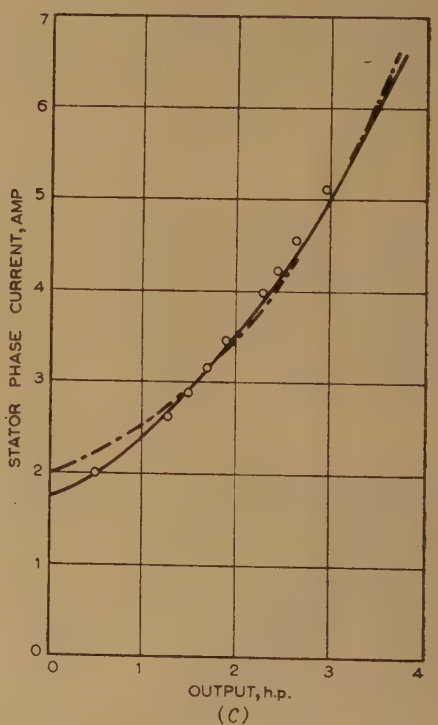
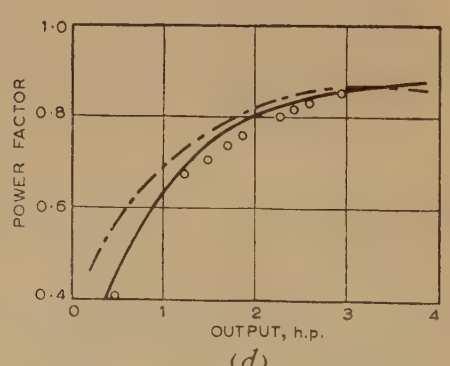


Fig. 1.—Equivalent circuit.









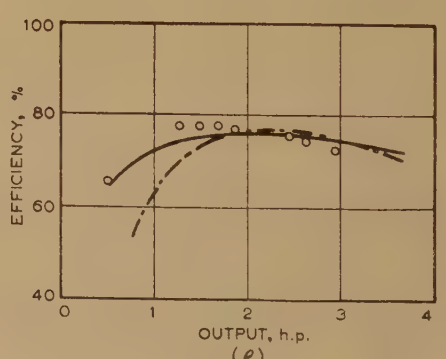


Fig. 2.—Motor characteristics.

○ Load test readings. —·—· No-load and locked-rotor test, $x_2' = x_1$. —— New method, $x_2' = 1{\cdot}34x_1$.

(*a*) Torque/slip.
(*b*) Slip/output.
(*c*) Stator-phase-current/output.
(*d*) Power factor/output.
(*e*) Efficiency/output.

(5) RESULTS

The equivalent circuit is shown in Fig. 1. The equivalent-circuit constants obtained by the new method and by no-load and locked-rotor tests are shown in Table 1.

Table 1

EQUIVALENT-CIRCUIT CONSTANTS BY VARIOUS METHODS

	No-load and locked-rotor tests	New method
x_1, ohms	6·115	5·23
r_1, ohms	3·3	2·5
x_2', ohms	6·115	7·0
r_2', ohms	5·82	6·6
g, mhos	0·001 29	0·001 29
b, mhos	0·008 1	0·008 1

The performance of the induction motor is calculated by the following methods:

(*a*) Equivalent circuit using constants obtained by new method.
(*b*) Equivalent circuit by no-load and locked-rotor tests.
(*c*) Load test.

A comparison of performance obtained by all three methods is shown in Fig. 2.

(6) CONCLUSIONS

It can be seen that the performance characteristics calculated by the new method lie very near to the actual load-test results. The performance calculated by no-load and locked-rotor tests give optimistic results. It is obvious that the method of dividing the total reactance equally between the stator and rotor is not very accurate because of the difference in winding structure of the stator and rotor, especially in the case of squirrel-cage machines. The method developed here, however, serves to allocate the reactances between stator and rotor more accurately.

In the new method the flux distribution measured is at the root of the stator teeth. This flux distribution is used in calculating the voltage induced in the stator. This is possible because of the following assumptions:

(*a*) The stator slot leakage flux and zigzag leakage flux are small in comparison with the mutual flux, and hence can be neglected.

(*b*) The effects of distortion on the air-gap flux waveshape due to fringing, zigzag and belt leakage can be neglected.

(*c*) The fundamental current in an induction motor produces a fundamental m.m.f. rotating at synchronous speed and several harmonic m.m.f.'s rotating at $-\frac{1}{5}$, $\frac{1}{7}$, etc., of the synchronous speed. Also the nth harmonic current produces fields rotating at n, $-n/5$, $n/7$, etc., times synchronous speed. When the stator windings are supplied with d.c., all these harmonic m.m.f.'s exist but are stationary with respect to the stator.

In an induction motor running at slip s, a field rotating at speed kn_s cuts the rotor at a speed $(k - 1 + s)n_s$. If direct current is supplied to the stator, and the rotor turns at sn_s, then the rotor cuts all the harmonic components of the m.m.f. wave at the same speed, sn_s. Hence conditions corresponding to that of an induction motor running at slip s are simulated correctly only for the fundamental m.m.f. with a speed n_s. It is expected that the error introduced due to this will be small and similar to that of differential leakage.

In normal well-designed induction motors the stator-slot leakage is about 1–2% and the differential leakage is about 2–3% of the mutual flux. In the machine designed and tested the values obtained by calculation are:

			ohms
Reactance of stator slot	..	..	0·925
Differential reactance ..	..	..	2·090
Magnetizing reactance ..	..	..	109

so that the above assumptions are justified. Further, the actual air-gap flux is less than the flux behind the stator teeth by the amount of the various stator leakages. This is to some extent offset by the fact that the flux measured by the new method does not include the radial flux passing through the depth of the stator slots. By calculating the permeance of the teeth and slots across their depth, it is found that the flux passing radially along the depth of a slot is $5{\cdot}919 \times 10^{-5}$ Wb, which is about 1·5% of the flux passing through the teeth ($349{\cdot}35 \times 10^{-5}$ Wb).

This new method of finding the reactance division between stator and rotor is laborious and at present of academic interest. It is hoped that such a study may lead to a more accurate and reasonable division of the total reactance between stator and rotor.

(7) ACKNOWLEDGMENTS

The induction motor was designed and built by the authors at the L.D. College of Engineering, Ahmedabad, India, and the investigation was carried out in the Electrical Engineering Department in connection with the dissertation of Mr. T. R. Subrahmanyan for M.E. (Electrical Machine Design) degree of Gujarat University.

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(9) APPENDICES

(9.1) Calculation of Equivalent D.C. Excitation

No-load phase current waveshape:

$$y = f(t) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

In most cases of electromagnetic induction without a commutator, there is no d.c. component and even harmonics are absent.

Therefore $y = A_1 \sin t + A_3 \sin 3t + A_5 \sin 5t + \ldots$

$$+ B_1 \cos t + B_3 \cos 3t + B_5 \cos 5t + \ldots$$

where the peak value of the nth harmonic is

$$C_n = \sqrt{(A_n^2 + B_n^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and the angle by which the nth harmonic lags the fundamental is given by

$$\alpha_n = \frac{1}{n} \tan^{-1}\left(-\frac{B_n}{A_n}\right) \quad . \quad . \quad . \quad . \quad (12)$$

Per-unit content of the nth harmonic:

$$p_n = \frac{C_n}{C_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The r.m.s. value of the no-load phase current will be

$$I_0 = \sqrt{\frac{I_{01\,max}^2 + I_{03\,max}^2 + I_{05\,max}^2}{2}} = \frac{C_1}{\sqrt{2}}(1 + p_3^2 + p_5^2 + \ldots)^{1/2}$$

$$. \quad . \quad . \quad . \quad (14)$$

from which the maximum value of the fundamental component will be

$$C_1 = (\sqrt{2})I_0/(1 + p_3^2 + p_5^2 + \ldots)^{1/2} \quad . \quad . \quad . \quad (15)$$

Knowing C_1, the maximum values of all the harmonics and their phase angles with respect to the fundamental can be determined. The effective direct currents required in each phase to produce the same flux distribution will be those given in eqns. (1)–(3).

(9.2) Details of Induction Motor

230 volts, 3-phase, 50c/s. Line current, 8·8amp. Phase current, 5·09amp. When delta connected for 4-pole operation, output is 3h.p. All winding terminals are brought out to a terminal board for multipole operation if required.

Design Calculations

Total resistance per phase	8·26 ohms
Total reactance per phase	11·55 ohms
Short-circuit power factor	0·658
Friction and windage loss	45 watts
Short-circuit current	17amp
No-load stator I^2R loss	49·2 watts
Magnetizing current	2·19amp = 44% of full-load current
Active component of no-load current	0·415amp
No-load current	2·23amp
No-load power factor	0·186
Full-load current	8·8amp
Full-load slip	13·75%
Full-load torque	13lb-ft

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THE APPLICATION OF TRANSISTORS TO PHASE-COMPARISON CARRIER PROTECTION

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(*The paper was first received 7th July, and in revised form 9th October*, 1958.)

SUMMARY

The paper shows the potentialities of the junction transistor when applied to phase-comparison carrier protection, and the flexibility of transistor circuits for the effective perfotmance of a number of different relaying functions. High-frequency high-power transistors, which are now available, make it possible to obtain the required level of carrier output power.

The paper also deals with the general aspects of a phase-comparison carrier system of protection, some appraisal being necessary because of the speed of operation and general performance of the equipment described. The most important of these aspects are the choice of the relaying quantities, and the effect of load current on the phase representing quantity, with its consequent effect on the minimum possible settings for earth faults. A sequence network is also described which produces all the relaying quantities simultaneously, using only three main current transformers. This sequence network has two important advantages: first, it does not impose any limitations on the relaying impedance, and secondly, means are provided for very easy variation of the proportions of the combined positive- and negative-sequence component output. The effect on the relaying system of a d.c. transient component in the fault current is analysed; a filter network is used to eliminate the d.c. transient and harmonic components, thereby producing uniform performance under differing fault conditions.

Two successive equipments have been built and tested under steady-state and transient conditions. The transient test results of the final equipment are given. Since the transistor is a temperature-sensitive device, exhaustive temperature tests have been carried out, and the results are summarized.

INTRODUCTION

The use of power-line carrier for communication purposes originated immediately after the 1914–18 War,[1] but it was not applied to protection until 1928, when A. S. Fitzgerald described his phase-comparison system.[2] The case for carrier protection is well established and has not changed greatly from the days of Fitzgerald. Viewed broadly, the situation is that, with long lines, the transference of information from one end to the other is uneconomic for a unit type of protection if conventional pilot wires are used and it is possible to justify the cost and complexity of transferring information by means of carrier channel(s) on the power conductors. Fitzgerald's system encountered severe practical difficulties; its successor was used for earth-fault protection only on a 200 kV line, the application being described by Stuffacher and Dolittle[3] in 1930. The principle of comparing phase by means of carrier was discarded after this in favour of directional-carrier (and later, more elaborate distance-carrier) schemes, only to be resuscitated in modern form towards the end of the 1939–45 War. On both sides of the Atlantic at this time, schemes were produced, e.g. those of Halman *et al.*,[4] Leyburn and Lackey[5] and McConnell *et al.*[6]

The expense and complexity of power-supply arrangements have always been a drawback with carrier equipment, and the idea of replacing normal electronic arrangements by transistors naturally commands attention; the advantages of the transistor in this respect have already been discussed. Feaster and Scheneman[7] have described equipment which uses a transistorized receiver and transmitter but with the normal functional elements of the carrier protection unchanged.

The problems of applying transistors to phase-comparison carrier protection have been investigated in the Power Systems Laboratory of the Manchester College of Science and Technology, and two successive sets of equipment have now been built and tested. It is the object of the paper to describe the principles involved in using transistors in this application, the functional arrangement of the complete equipment and the test results. There is no question of taking normal electronic carrier equipment and replacing it with transistor equivalents; substantial economy in function is possible quite apart from the inherent advantages associated with power drain, h.t. and heater supplies, and the final equipment has the following features of major interest:

(*a*) It is wholly electronic from the starting circuit onwards, with the exception of the final slave relay, and consists of a number of separate functional units each arranged as a plug-in sub-assembly. In particular, electromagnetic relay arrangements for control of carrier starting and also of tripping, which are a normal feature of valve-operated carrier systems, have been eliminated.

(*b*) Valves have been eliminated in all circuits including, as in the Potomac–Edison experiment,[7] the transmitter and receiver. The valve circuits of conventional carrier arrangements bear no affinity to the transistor circuits which have been used, and in many instances they have an entirely different functional role; transistors are used throughout as individual switches, as phase-inverters and/or isolating stages, or as component parts of trigger circuits, and only rarely as amplifiers and then in such a way that changes in gain are immaterial. The principles involved in the use of transistors in this application are thus substantially the same as those described earlier in the application of juction transistors to distance relays.[8,9]

(*c*) Means have been adopted for ensuring uniform speed of operation for any fault within the protected section, irrespective of d.c. asymmetry in the wave of fault current. These arrangements are not electronic in nature but have been described since they are an integral part of the equipment and contribute to its high level of performance and very fast operating time.

(*d*) A method has been adopted for utilizing inter-tripping facilities in the event of marginal conditions developing; these come into use for certain phase angles and fault currents, and in the event of fault current being fed from one end of the protected section only.

(*e*) The system is designed for automatic resetting subsequent to fault clearance.

(1) PROBLEMS OF PHASE-COMPARISON CARRIER PROTECTION

In its simplest form the phase-comparison carrier system may be regarded as a single-phase comparison of two signals derived from all three phases at each end of the protected section. The signal at each end is derived from current transformers through a network giving a convenient combination of symmetrical-component quantities. Information, i.e. the phase angle of the derived current at each end of the system, is transmitted by a carrier signal modulated by square waves of equal mark/space ratio; the carrier is thus injected into the power lines at each end simultaneously in blocks corresponding to alternate half-

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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cycles at the power frequency. During the half-cycles at each end when carrier is not being transmitted, tripping is locally effected unless it is blocked by carrier received from the remote end. An arrangement is commonly adopted in which the blocks of modulated carrier injected at each end are in phase opposition for the case of through fault; blocking carrier is thus received at each end during its tripping half-cycle, and tripping does not take place in this condition. In the ideal case, the blocks of modulated carrier appearing on the line from each end are coincident for the case of an internal fault; the circuit-breakers will operate since no blocking signal is received during a tripping half-cycle at either end. These arrangements are indicated in Fig. 1.

(1.2) Choice of Relaying Quantities

The effectiveness of a phase-comparison carrier system is greatly dependent on the choice of the relaying quantities and the method of their derivation. The arrangements at each end should provide for the detection of all faults, balanced and unbalanced, which can occur on the system; the derived single-phase quantity which is used to modulate the carrier must faithfully represent, for any combination of load and fault currents, the phase angle of the line current at each end with respect to some convenient datum.

Positive- and negative-sequence outputs from sequence networks are commonly used for starting purposes, whilst the output of a summation transformer or a combination of sequence

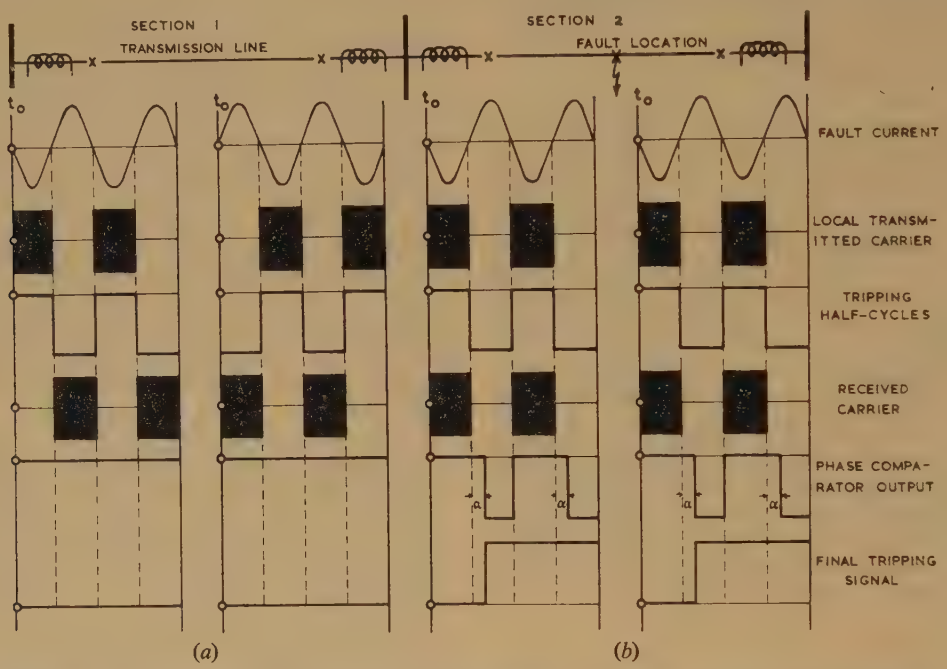


Fig. 1.—Fundamental arrangements of carrier and modulating signals for a phase-comparison carrier system of protection.
α = Angle of stability.
(*a*) External fault condition. (*b*) Internal fault condition.

(1.1) Unwanted Phase Shifts

Clearly any phenomena which cause unwanted phase shifts between the currents at each end of the system will raise fundamental difficulties with this type of protection, since the phase comparator, which is the main relaying element, has the function of producing an output for tripping when the phase displacement between the modulated blocks of carrier exceeds a given angle. This angle, under through-fault conditions, should be large enough to minimize the effect of spurious phase shifts, but should be small enough to avoid failure to trip under internal fault conditions. Unwanted phase shifts arise from the power system in two main ways:

(*a*) If the line length is great, the time of transmission of the carrier signal from one end of the protected section to the other is significant, since it corresponds to a phase shift of about 1° for each 10 miles of line length.

(*b*) The charging currents of the line produce significant phase shifts between the currents at each end of the protected section, an effect which is more marked at high voltages and low fault currents.

In addition to (*a*) and (*b*), the carrier apparatus can also cause very small phase shifts; this is particularly true for the coupling arrangements between the carrier set and the transmission line. All these factors usually lead to a phase-angle setting for the phase comparator of approximately 30°.

quantities is used for the signal representing phase. In the equipment described, positive- and negative-sequence quantities are used for starting purposes under balanced and unbalanced faults, respectively, whilst the phase-representing quantity takes the form

$$I = MI_2 + NI_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $M > 1$ and $N = \pm 1$, and the suffixes 1 and 2 denote positive and negative phase sequence, respectively.

The merits of particular choices for the magnitudes and signs of the coefficients M and N are fully discussed in Appendix 9.1.

(1.3) Starting

Adequate arrangements must be made to start the carrier system at minimum fault conditions, and at the same time ensure that it is not operated at maximum load conditions. Response to the amplitude only of the negative-sequence signal is sufficient for unbalanced faults, whereas response to both amplitude and rate of increase of positive-sequence output is necessary for balanced faults. There are two settings for each of the positive- and negative-sequence starting arrangements: a low setting is used for starting carrier and a high one for controlling tripping. These arrangements are all that is necessary to ensure that carrier is established on the line before tripping is allowed.

(2) DERIVATION OF THE PHASE-MEASURING AND STARTING QUANTITIES

The sequence network used to derive the relaying quantities from the main delta-connected current transformers is shown in Fig. 2. The three operating quantities, the positive-, the negative- and the combined positive- and negative-sequence components, are derived simultaneously by the same network, which is supplied from three current transformers only. The operating virtues of this network are that the impedances presented across each pair of output terminals can have any value from zero to infinity provided that they are equal; only the proportionality of the output differs with the impedance chosen, and the proportion of the negative-sequence component in the combined output can readily be altered by variation of r. The value of M in eqn. (1) varies in accordance with the relationship

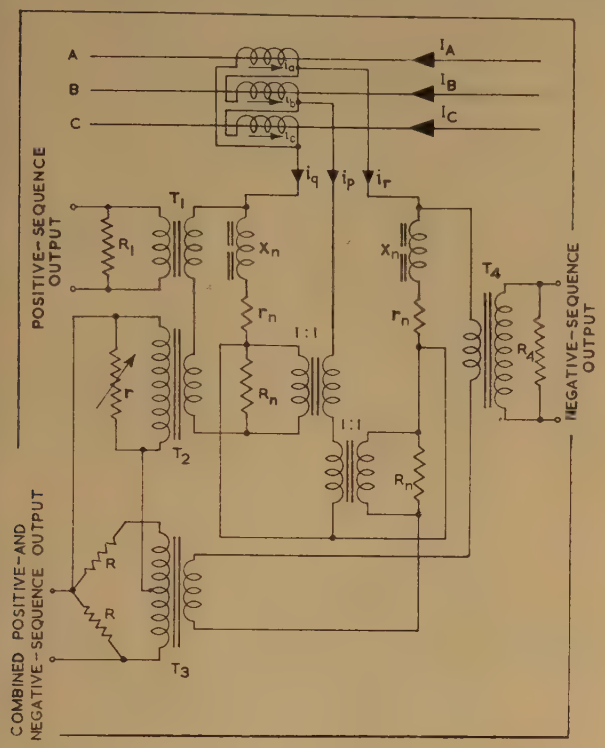


Fig. 2.—Combined positive- and negative-sequence network.

$$M = 2 + \frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

as demonstrated in Appendix 9.2.

The design of the transformers for matching the main electronic relaying system to the sequence network depends on the following factors:

(*a*) The negative-sequence setting for starting.
(*b*) The positive-sequence setting for starting.
(*c*) The values chosen for M and N.
(*d*) The minimum voltage required to operate the starting and squaring circuits.

A procedure for the design of these transformers is given in Appendix 9.2.

(3) OVERALL OPERATING PRINCIPLES

Fig. 3 shows the equipment at one end of a protected section. The outputs from the delta-connected secondary windings of the main current transformers are fed to a sequence network which produces independent positive- and negative-sequence outputs.

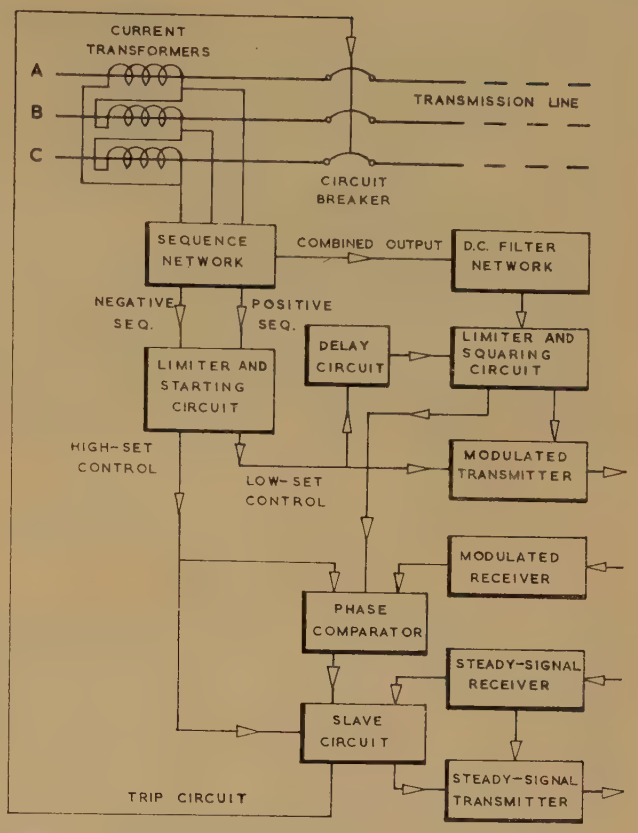


Fig. 3.—Schematic of the equipment for one carrier terminal.

These components are fed in parallel to the starting circuit through isolating diodes, whilst a combination of them is fed to the squaring circuit through a filter which eliminates any harmonic and d.c. transient which may be present. The starting circuit will pick up when the amplitude of the negative-sequence component exceeds a predetermined level, or, alternatively, when both the amplitude and rate of increase of the positive-sequence component exceed a predetermined level. The only difference between these two starting arrangements is that, with negative-sequence starting, reset only occurs after fault clearance, whilst the other method has automatic reset after a predetermined time unless reset has occurred earlier as a consequence of fault clearance. When the starting circuit picks up, it produces four step-function outputs, as follows:

(i) Two high-set outputs of opposite polarity; one fed to the phase-comparator and the other to the slave circuit.
(ii) Two low-set outputs of opposite polarity; one fed to the modulated-carrier control circuit and the other to a delay circuit.

The starting input signal is preponderant throughout the apparatus; each individual unit which is controlled by a starting signal does not respond to any other input(s) unless starting has occurred. The squaring circuit produces two square-wave outputs of opposite polarity; one of these is fed to the modulated-carrier control circuit, where it causes the transmission of square-wave-modulated carrier provided that the starting input exists, whilst the other is fed to the phase comparator in order to be compared with the square wave derived from the transmitted signal from the remote end. The phase comparator decides whether the fault is internal, and if so, produces an output. This output is fed to the slave circuit where, again, the starting signal must have been received previously, and tripping takes place.

The starting-circuit signal to the delay circuit causes this, in its turn, to produce a time-lagged output sufficient to allow

clearance in the normal way. The delay-circuit output is fed to the last stage of the squaring circuit, where it stops only the square wave fed to the modulated-carrier control circuit. This, together with the previous existence of the starting signal, causes continuous carrier to be transmitted which blocks tripping at the remote end, thus safeguarding against false tripping when an external fault is being cleared. The same sequence of events then occurs at the remote end and continuous carrier is transmitted to the near end with the same effect.

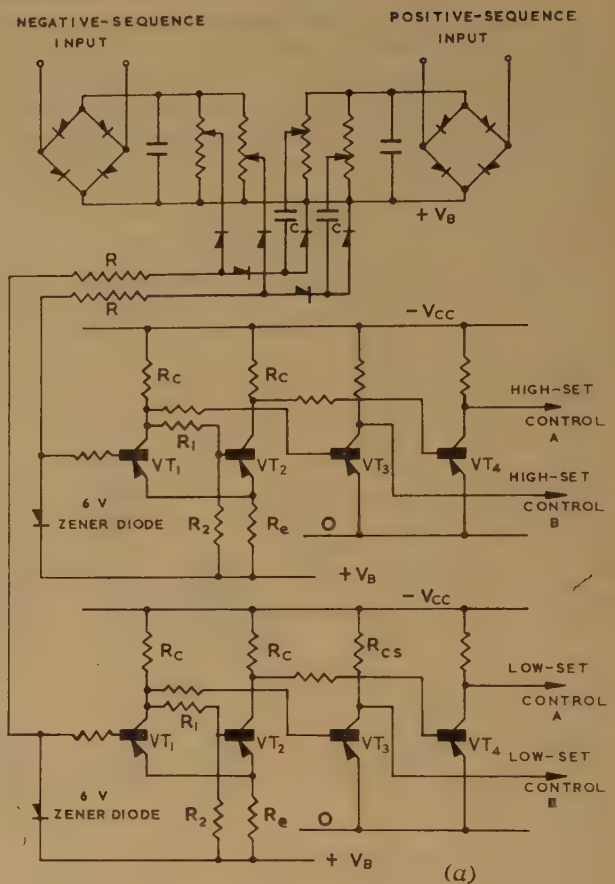
To provide for the special circumstances indicated in (*d*) in the Introduction, an intertrip transmitter and receiver are added at each end. At either end the transmitter is started by a signal fed to its input from the slave circuit. The slave circuit at the remote end is operated by this intertrip carrier signal, which has the additional function of stopping the remote-end intertrip carrier signal, thereby preventing interlocking and enabling the system to reset after fault clearance.

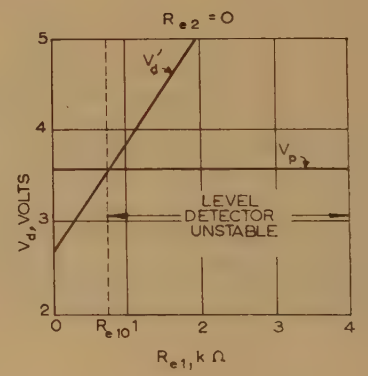
(4) BEHAVIOUR OF INDIVIDUAL ELEMENTS OF THE SYSTEM

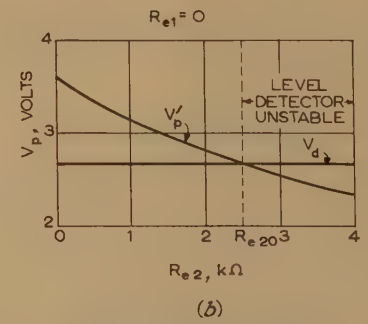
(4.1) The Starting Circuit

As mentioned in Section 3, the starting circuit picks up in response either to the amplitude of the negative-sequence component of the fault current for an unbalanced fault, or to both the amplitude and rate of increase of the positive-sequence component for a balanced fault. The starting-circuit arrangement is shown in Fig. 4(*a*), where each of the negative- and positive-sequence components, as produced by the sequence network of Fig. 2, is rectified by a full-wave rectifier bridge. The rectified d.c. outputs corresponding to the negative-sequence component are taken, at high and low levels of voltage, from the potentiometer which controls settings, and fed directly to the low- and high-set starting circuits, respectively, through isolating diodes; the rectified d.c. outputs corresponding to the positive-sequence component are fed to pulse circuits, each consisting of a capacitor C and a discharging diode shunting this capacitor to the $+V_B$ supply. Any sudden change in the positive-sequence input signal is instantaneously produced at the outputs, subsequent decay of these outputs signals taking place as the capacitors charge. The diodes shunting the capacitors to the $+V_B$ supply cause them to discharge rapidly after fault clearance, thereby making the pulse circuits ready to perform their functions immediately in any subsequent operation. The outputs of the impulse circuits are fed to the low- and high-set starting circuits through isolating diodes in the same manner as those corresponding to the negative-sequence component.

The low- and high-set starting circuit arrangements are identical, apart from being fed from the low- and high-voltage tappings, respectively, on the setting potentiometer. Each circuit consists of a level detector which is a common-emitter trigger circuit incorporating transistors VT_1 and VT_2 [Fig. 4(*a*)], followed by an output stage incorporating transistors VT_3 and VT_4. Each level detector and output stage uses two transistors, i.e. a total of eight, together with four isolating diodes, two discharge diodes and the eight diodes which form the two rectifier bridges. The drop-out voltage of the level detector, V_d, is usually less than its pick-up voltage, V_p. However, these can be made closer or equal by the insertion of either a resistor R_{e1} in series with the emitter of VT_1, or R_{e2} in series with the emitter of VT_2 [Fig. 4(*a*)]. Fig. 4(*b*) shows the relation of R_{e1} and R_{e2} with V_p and V_q. The level detector, in this case, uses pick-up valves slightly larger than those for drop-out, thereby allowing for a certain percentage of ripple in the rectifier voltage and at the same time avoiding starting-circuit 'chatter' for marginal faults.







(*b*)

Fig. 4.—Starting circuit.

(*a*) Arrangement of starting circuit.
(*b*) Effect of R_{e1} and R_{e2} on V_p and V_q.

$R_c = 6{\cdot}8\,k\Omega$ $R_2 = 39\,k\Omega$
$R_e = 2{\cdot}2\,k\Omega$ $V_{cc} = 12$ volts
$R_1 = 15\,k\Omega$ VT_1 and VT_2 are type OC71

(4.2) D.C. Filter Network and Squaring Circuit

It is extremely important that two isolated steep-sided square-wave pulses of unity mark/space ratio should be derived; one for modulation and the other as an input to the phase comparator. If direct current is present in the output ($MI_2 + NI_1$) of the sequence network, it can be shown (Appendix 9.3) that failure to obtain equal mark/space ratios does not impair correct operation of the phase-comparison system but may cause a time delay of one cycle, particularly if the d.c. time-constant is long.

Since the protective system under discussion is inherently very fast, it follows that the elimination of transient time delay would make a large percentage reduction in the overall operating time. To make this improvement, direct current is filtered out between the sequence network and the squaring circuit. The filter arrangement adopted and its analysis appear in Appendix 9.3; its performance is illustrated in Fig. 16(*b*).

(4.3) Carrier Control and Modulation

The carrier control and modulation consist of the oscillator and the control arrangements for both modulated and continuous carrier. Control is accomplished through the use of transistors with a common-emitter circuit, as shown in Fig. 5. Transistors

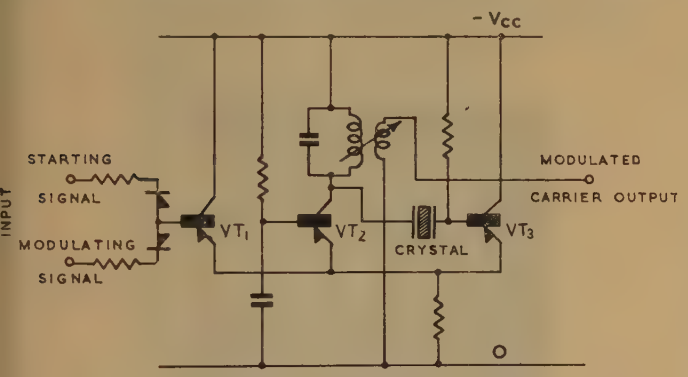


Fig. 5.—Basic transistor arrangement for carrier control and modulation.

VT_2 and VT_3 behave as the oscillator when transistor VT_1 is cut off. When transistor VT_1 is not cut off, a heavy current is drawn through the common resistor, and the oscillator stops.

(4.4) Phase Comparator

The phase comparator, which is the main relaying element of the protective system, consists of a coincidence stage controlled by the starting input, followed by an integrating circuit and a level-detector/output stage, as shown in Fig. 6(*a*). The basic arrangement of the coincidence stage is shown in Fig. 6(*b*); three inputs are fed to the base of the transistor through diodes. Input 1 is from the starting circuit, and is normally negative, thus maintaining the transistor 'on' irrespective of inputs 2 and 3. When the starting circuit picks up, input 1 assumes zero potential, thereby allowing comparison in phase of the signals 2 and 3 applied to the remaining terminals. Input 2 is the local square wave and input 3 is the received square wave from the remote end. When either of these square waves is of negative potential, the transistor still conducts. It is clear that, with both of them positive or zero and with the starting input also zero, the transistor will be cut off; the result is that output negative pulses are obtained of a duration equal to the angle of coincidence of 2 and 3. The integrating circuit may be a straightforward arrangement of capacitor charging through a resistor during intervals when the transistor is cut off, or if greater accuracy

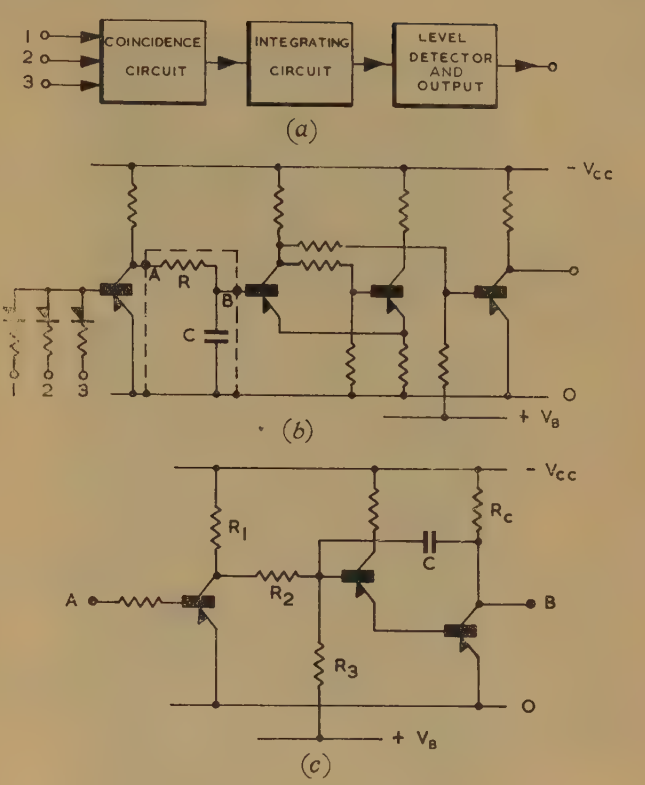


Fig. 6.—Phase-comparator circuit.
(*a*) Block schematic.
(*b*) Basic arrangement for detecting coincidence.
(*c*) Linear integrating circuit.

and linearity are needed, an integrating amplifier may be used, as shown in Fig. 6(*c*). This operational amplifier has a high gain and low input impedance with negative capacitive feedback, and must be preceded by a phase-inverting stage so that the output voltage changes from zero to negative values. The level detector is the same as the one used throughout the system. However, in this particular application, the relation between the pick-up voltage, V_p, and the drop-out voltage, V_d, must satisfy the condition $(V_p - V_d) \geqslant i_{b\,min} r_b$, where r_b is the transistor base resistance and $i_{b\,min}$ is the base current required to make the input transistor conduct fully.

(4.5) Slave Circuit

The basic arrangement of the slave circuit, which is shown in Fig. 7, consists of three main sections:

(*a*) A switching transistor VT_1, which maintains the slave circuit in a normally unenergized condition. When the starting input is applied to its base, the circuit is then in a 'ready' condition. It also follows that resetting will automatically take place after fault clearance, since the normal signal from the starting circuit, i.e. when the system is healthy, switches off transistor VT_1.

(*b*) The asymmetrical bistable circuit consisting of transistors VT_2 and VT_3. These are arranged so that, with the circuit first energized, transistor VT_3 conducts whilst VT_2 is cut off. When a negative tripping pulse is obtained from the phase-comparator circuit and applied to VT_2, it starts to conduct and VT_3 cuts off; the slave relay is thus energized for final tripping. The input capacitor C_1 ensures circuit stability against parasitic pulses during fault conditions.

(*c*) Transistor VT_4, which is normally cut off. If an inter-

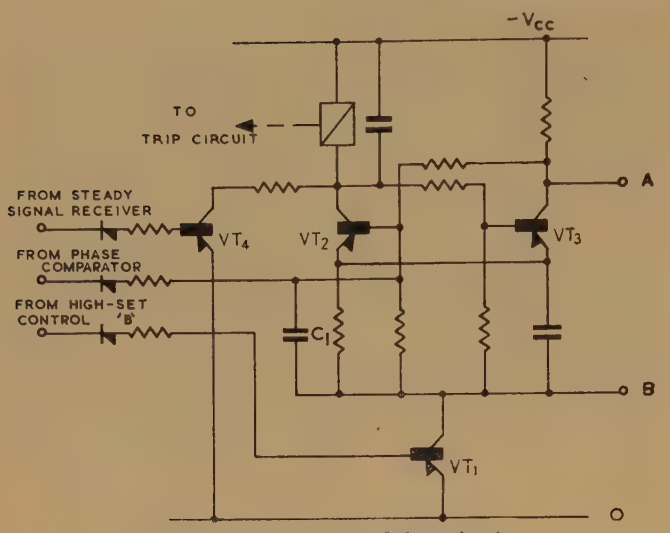


Fig. 7.—Arrangement of slave circuit.

tripping signal is received, a negative voltage is applied to the base of VT_4; it thus conducts and operates the slave relay irrespective of the local conditions.

When the slave circuit picks up, an output step function is produced between terminals A and B, which is used to start the intertrip transmitter.

(5) SYSTEM PERFORMANCE AND TESTING

Two successive sets of equipment have been built and tested under steady-state and transient conditions. The first equipment, however, never had the complete input arrangement of 3-phase current transformers and sequence network, and was tested on a single-phase basis. It served satisfactorily as a prototype for the various individual circuits which comprise the electronic part of the equipment.

The high-speed relay test bench installed in the Power Systems Laboratory was used for testing. Phase shifts down the protected line have been simulated by capacitors situated between the two sets of current transformers, supplying the equipment at each end, and carrier-signal attenuation up to 40 dB has been provided.

Figs. 8–11 illustrate the performance, under exhaustive laboratory conditions, of the two carrier ends; a third set of equipment having basic units identical with those in the one described, but equipped with full test and servicing facilities, is at present being constructed by an industrial concern and will be used for full-scale field testing.

(5.1) Starting-Circuit Pick-Up and Carrier Signals

The starting-circuit pick-up is virtually instantaneous, as may be seen from Fig. 8(*b*) in comparison with the fault-current signal [Fig. 8(*a*)]. Fig. 8(*c*) shows the initiation of the modulated carrier at each end of the system; at each end modulated carrier is replaced by continuous carrier for blocking purposes after a controlled time delay.

(5.2) Oscillograph Results for No-Trip Condition

The oscillographs are shown in Figs. 9(*a*), (*b*) and (*c*). Fig. 9(*a*) shows the carrier signals from each end of the system during the period of modulation. Figs. 9(*b*) and (*c*) show the inputs to the level-detector stage of the phase comparator, using an *RC* and a linear integrator, respectively. They are insufficient for tripping.

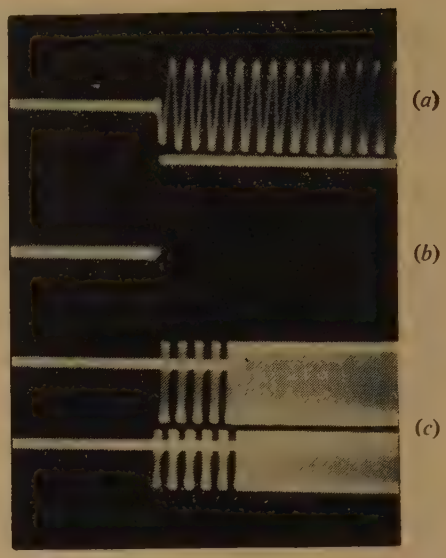


Fig. 8.—Carrier starting.

(*a*) Fault-current wave.
(*b*) Starting-circuit pick-up corresponding to fault-current inception.
(*c*) Modulated and continuous carrier from each end of the system.

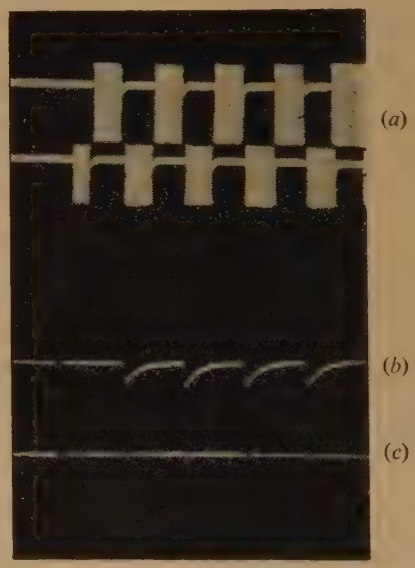


Fig. 9.—Oscillographic results for no-trip conditions.

(*a*) Modulated carrier, each end of the system, for no-trip condition.
(*b*) Level-detector input from *RC* integrator.
(*c*) Level-detector input from linear integrator.

(5.3) Oscillograph Results for Trip Condition

Fig. 10(*a*) corresponds to Fig. 9(*a*), both being for the ideal case of no phase shift down the transmission system. Figs. 10(*b*) and (*c*) show the waveforms corresponding to Figs. 9(*b*) and (*c*), respectively, which are now appropriate for tripping. Fig. 10(*d*) shows the output of the phase comparator to the slave circuit, and Fig. 10(*e*) illustrates the tripping time. The upper trace of Fig. 10(*e*) shows the fault current from the moment of inception to interruption through the slave-relay contacts; it can be seen that the overall operating time is approximately two cycles. The lower trace shows the intertrip carrier, which is started by the slave circuit and through the relay contacts. The interval from the inception of the fault current to the first

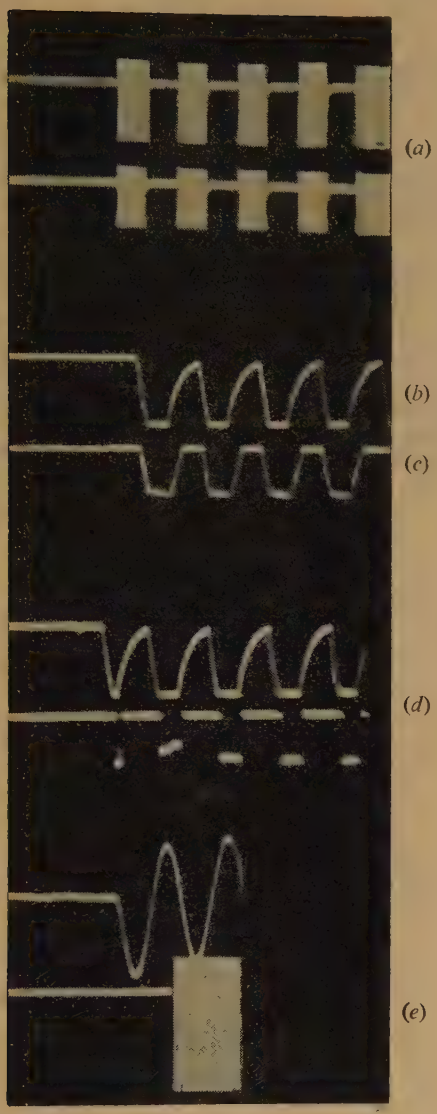


Fig. 10.—Oscillographic results for trip conditions.
(*a*) Modulated carrier from each end of the system for trip condition.
(*b*) As for Fig. 9(*b*), but for trip condition.
(*c*) As for Fig. 9(*c*), but for trip condition.
(*d*) Output from phase comparator to slave circuit for trip condition.
(*e*) Time of operation.

appearance of the intertrip-transmit signal thus indicates the time of operation of the protective system, excluding the time of operation of the slave-relay element itself. This time is clearly of the order of 15 millisec, or $\frac{3}{4}$ cycle, and is only attainable through use of the d.c. filter described above.

(5.3) Balanced Faults

For the initiation of operation during balanced faults, rate-of-increase starting is employed. The pulse inputs to the starting circuits are shown in Fig. 11(*a*), and the different durations of the high-set and low-set pick-up periods in Fig. 11(*b*). The low-set signal which starts the carrier of Fig. 11(*c*) is of longer duration than the high-set signal which permits tripping, as can be seen from Fig. 11(*d*). Fig. 11(*d*) thus shows simultaneously the time of operation, the period during which tripping is allowed as indicated by the blank interval, and the total period of carrier transmission.

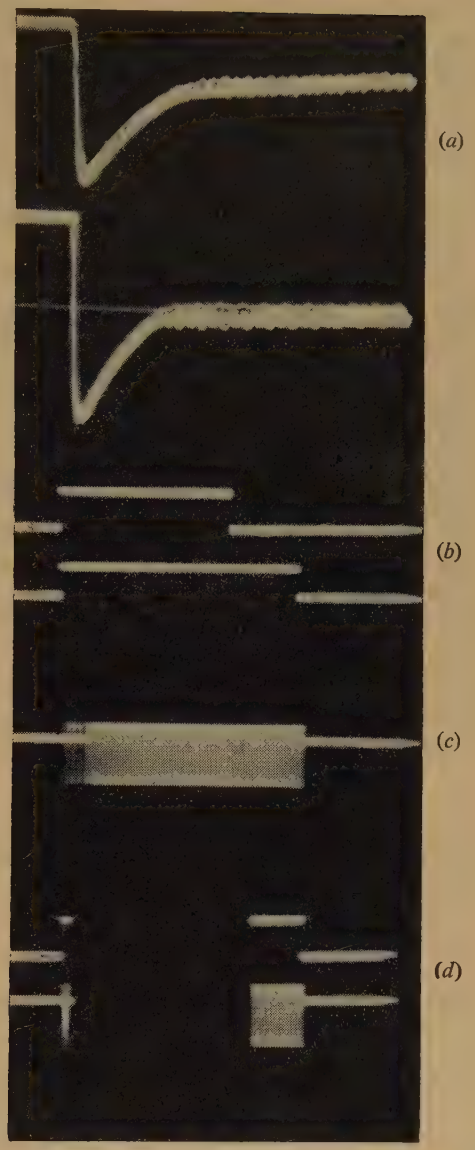


Fig. 11.—Oscillographic results for balanced fault conditions.
(*a*) Pulse inputs to low-set and high-set starting circuits, respectively.
(*b*) High-set and low-set starting-circuit outputs.
(*c*) Control of carrier by low-set output.
(*d*) Time and duration of operation.

(5.4) Temperature Performance

The elements most susceptible to temperature change are the level detectors, and hence, in particular, the phase comparator. Other features of importance are the oscillator-frequency stability and power-output stability of the power amplifier with temperature variation. There is also the question of overall performance of the system with temperature.

With any of the level detectors, the pick-up level increases with rise of temperature, from 3·65 to 3·8 volts for 20 to 50° C change. This is due to an increase in I_{c0} with rise of temperature, with consequent increase in the bias voltage. To overcome this effect, compensation has been introduced, and the pick-up level sustained at a constant value for the same 30° C temperature change.

Temperature effects on the crystal oscillator were negligible, the frequency change being 3 c/s in 100 kc/s for 30° C change.

The power amplifier needs a minimum input drive to give its full output, Originally using type OC71 transistors in the

master-oscillator circuit, a fall in power output of 19% occurred for a change of temperature from 20 to 50°C; with type OC45, the corresponding change was 2%, which was considered to be acceptable.

From the point of view of overall system performance there is a distinct advantage in operating the system at a reduced voltage, say 8 volts, since this greatly minimizes the tendency of the transistor collector current to 'creep' at high temperatures.

(6) CONCLUSIONS

The results set out in the paper demonstrate the feasibility of using transistors as circuit elements in a carrier scheme of protection. The system of protection which has been devised is suited to all the abnormal power-system conditions which may be experienced as shown in the Appendices. No transistor failures have been experienced throughout the exhaustive testing, and this supplements the very encouraging results from the transistor life-test experiments being carried out in the Power Systems Laboratory.* The functional use of the transistor mainly as a switching on-off element is clearly very satisfactory.

The times of operation are well within normal specifications, even allowing for time of operation of a slave relay, and as shown in the Appendices, they can readily be made independent of system transient conditions.

A carrier protective system designed to the principles described in the paper is now being manufactured to industrial specifications, and the next stage of field testing under actual system conditions can be anticipated.

(7) ACKNOWLEDGMENTS

The authors wish to acknowledge their appreciation of helpful discussions both with their colleague Mr. P. Mathews and with Mr. W. A. Cowin.

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* Discussion on References 8 and 9.

(9) APPENDICES

(9.1) Phase-Representing Quantity

The output quantity for representing the fault current in phase can be one of the following combinations of sequence currents:

(i) Output $\propto I_1$
(ii) Output $\propto MI_2 + KI_0$
(iii) Output $\propto MI_2 + NI_1$
(iv) Output $\propto KI_0 + NI_1$
(v) Output $\propto AI_2 + BI_0 + NI_1$

Of these, (iii) has advantages and has been chosen for the system described in the paper. For an output proportional to $MI_2 + NI_1 = I_m$, considering all possible combinations for $N = \pm 1$, $M > 1$ we have:

(*a*) *3-phase faults.*—The output is proportional to I_1. The relay setting in this case must exceed 100% to give correct phase representation at full load, but this high setting is already necessary to ensure non-operation of the protection at full loads.

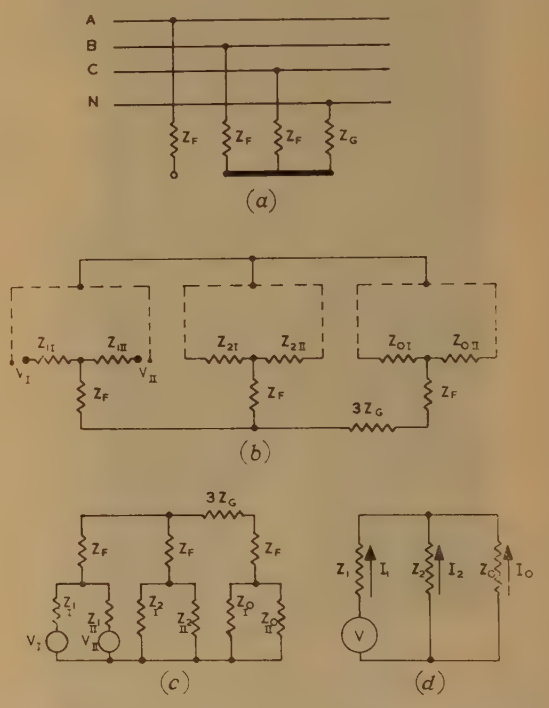


Fig. 12.—Sequence networks for 2-phase-to-earth fault.

(*b*) *2-Phase Faults and 2-Phase-to-Earth Faults.*—Fig. 12 shows the interconnection of the sequence circuits for this type of fault. Assuming $X_1 = X_2$ and neglecting resistance, it can be shown that:

For phase B–C–neutral faults (*A* being the reference phase),

$$\frac{|I_m|}{|I_F|} = \frac{(M-N)\frac{X_0}{X_1} - N}{\sqrt{3}\sqrt{\left[1 + \frac{X_0}{X_1} + \left(\frac{X_0}{X_1}\right)^2\right]}} \quad \ldots \quad (3)$$

and for phase A–B–neutral and phase A–C–neutral faults,

$$\frac{|I_m|}{|I_F|} = \frac{\sqrt{\left[N^2 + (MN + 2N^2)\frac{X_0}{X_1} + (M^2 + MN + N^2)\left(\frac{X_0}{X_1}\right)^2\right]}}{\sqrt{3}\sqrt{\left[1 + \frac{X_0}{X_1} + \left(\frac{X_0}{X_1}\right)^2\right]}} \quad \ldots \quad (4)$$

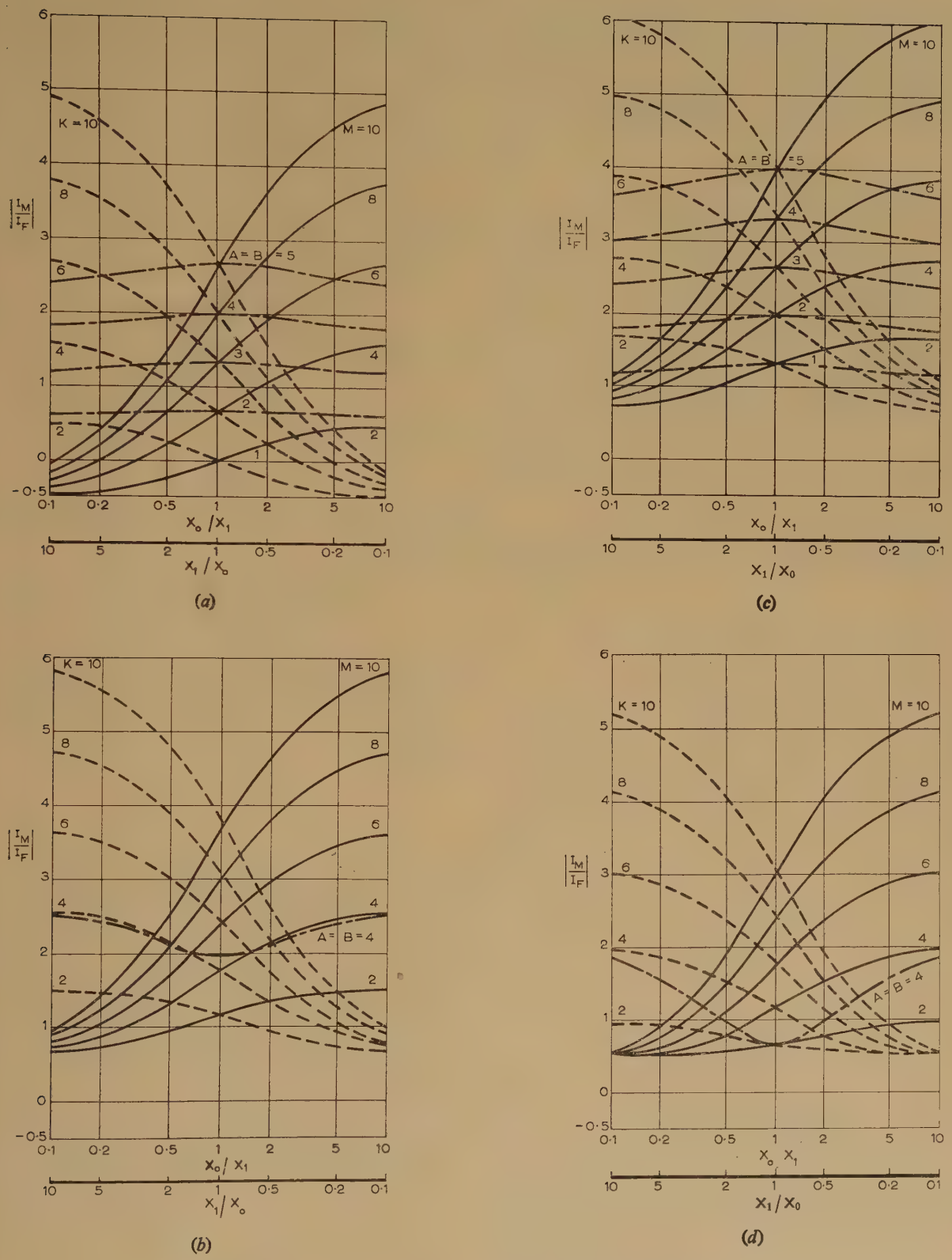


Fig. 13.—Curves for the choice of sequence-current combinations.

(*a*) $N = +1$, phase C phase B–N fault.
(*b*) $N = +1$, phase A phase B–N or phase A phase C–N fault.
(*c*) $N = -1$, phase C phase B–N fault.
(*d*) $N = -1$, phase A phase B–N or phase A phase C–N fault.

For $N = +1$, eqn. (3) becomes zero for $X_0/X_1 = 1/(M-1)$, a case which may arise in practice. For $N = -1$, eqn. (3) cannot be zero for all possible values of X_0/X_1; this latter value for N will therefore be used.

Figs. 13(*a*), (*b*), (*c*) and (*d*) show $|I_m|/|I_F|$ for various values of M, and for $N = +1$ and $N = -1$, respectively.

(*c*) *Earth Faults.*—For phase A-to-neutral faults,

$$\frac{|I_m|}{|I_F|} = \frac{1}{3}(M+N) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and for phase B-to-neutral or phase C-to-neutral faults,

$$\frac{|I_m|}{|I_F|} = \frac{1}{3}\sqrt{(M^2 - MN + N^2)} \quad . \quad . \quad . \quad . \quad (6)$$

$|I_m|/|I_F|$ in eqn (5) will always be smaller than its value in eqn. (6), for the same value of M, and $N = -1$.

Taking the case of the minimum fault condition and assuming that the minimum setting for starting is x, then $I_{Fmin} = xI_{fl}$.

Full-load current, superimposed on the minimum fault current, can have any phase angle with respect to I_m. The load currents at the ends *I* and *II*, as presented to the relaying system, are in phase opposition.

For external faults, the load current will not affect the stability of the relaying system, since the current distribution for this case is almost the same at both ends of the line.

For internal faults, I_{m1} at end *I* and I_{m2} at end *II* are approximately in phase, or there may be a small phase angle, θ, between them. With reference to Figs. 14(*a*) and (*b*), it can be seen

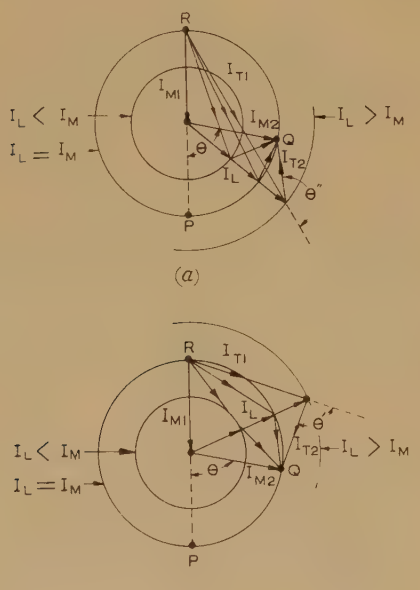


Fig. 14.—Effect of load current during internal fault, for two ranges of phase angles of load current.

that, under this condition, the phase angle, θ, increases for the higher load currents. When $|I_{m1}| = |I_{m2}| = |I_L|$, the resultant phase angle, after taking load current into account, is equal to $(90 + \theta/2)$ for phase angles of I_L between P and Q, and equal to $(90 - \theta/2)$ for I_L between *Q* and *R*. Such a condition is the maximum to be allowed, since if $|I_L| > |I_m|$ the system may fail to trip in the case of internal faults. If $|I_{m1}| > |I_{m2}|$, the maximum permitted value for $|I_L|$ is that of $|I_{m2}|$, in which case the angular deviation will be less than that for the case $|I_{m1}| = |I_{m2}| = |I_L|$. Where such increased angles due to full load are objectionable, values of $|I_{fl}|/|I_{mmin}|$ of less than unity must be used.

During internal faults, the cases of I_m and I_{fl} summing to zero at one end are not objectionable, since this allows instantaneous tripping at both ends of the protected line.

Assuming the chosen value

$$|I_{fl}|/|I_{mmin}| = y \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

for minimum fault condition,

$$|I_{mmin}| = (M-1)/3|I_{Fmin}| \quad . \quad . \quad . \quad . \quad (8)$$

where I_{Fmin} is the minimum fault current.

From eqns. (7) and (8),

$$|I_{fl}| = y|I_{mmin}|$$
$$= y|I_{Fmin}|(M-1)/3 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

If the minimum setting for starting is x,

$$|I_{Fmin}| = x|I_{fl}| \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

From eqns. (9) and (10),

$$|I_{fl}| = yx|I_{fl}|(M-1)/3$$

or

$$x = 3/y(M-1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Eqn. (11) gives the relation between x, the minimum possible setting of the starting circuit for earth faults, the value of M and $y \leqslant 1$.

(9.2) Selection and Control of Positive and Negative Phase-Sequence Currents

With reference to Fig. 2, the delta currents, i_p, i_q and i_r, fed to the sequence networks are related to the secondary currents i_a, i_b and i_c, as shown in Fig. 15(*a*).

The currents, I_1' and I_2', passing through the positive- and negative-sequence sides of the sequence network, respectively, are given by

$$I_1' = K(i_p + i_q \angle 60) \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$I_2' = K(i_p + i_r \angle 60) \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where K is a constant, depending on the loading impedance, whose values should be equal at both sides of the network. It is obvious from Fig. 15(*a*) that the phase angle between the positive- and negative-sequence outputs, I_1' and I_2', is changed by 180° from its original value between I_1 and I_2, on the primary side of the current transformers. Thus I_1' must be added to MI_2' at the output of the network in order to obtain $(MI_2 - I_1)$.

The combined positive- and negative-sequence output is obtained by adding the outputs of transformers T_2 and T_3 of Fig. 2 in one arm of a bridge composed of the two resistors R and the centre-tapped transformer T_3, as shown in Fig. 2. The bridge connection is used to avoid feedback between the positive- and negative-sequence outputs. The transformers T_2 and T_3 have the same turns ratio, which is of the order of 1 : 20.

With reference to Fig. 15(*b*), for any value of r connected across the secondary winding of T_2, the output is given by

$$V_0 \propto I_2' R + I_1' \frac{rR}{R+2r}$$

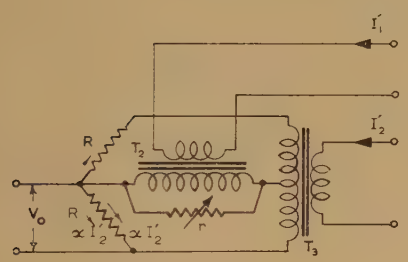
$$\propto \left(2 + \frac{R}{r}\right) I_2' + I_1'$$

or

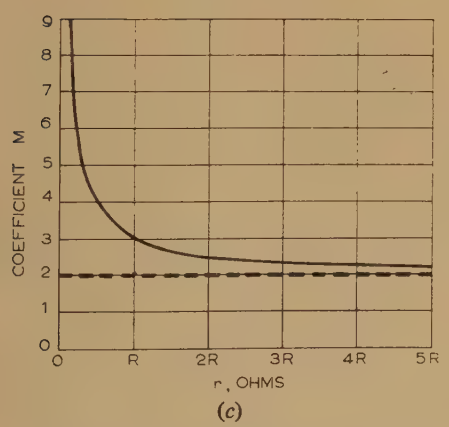
$$V_0 \propto \left(2 + \frac{R}{r}\right) I_2 - I_1 \quad . \quad . \quad . \quad . \quad . \quad (14)$$



(a)



(b)



(c)

Fig. 15.—Phase-representing quantity.

(*a*) Vector relationships for sequence network.
(*b*) Bridge connection for combined negative- and positive-sequence output.
(*c*) Variation of M with r.

From eqn. (14) it is clear that M is given by

$$M = 2 + \frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Eqn. (2) is represented in Fig. 15(*c*), from which it can be seen that M has a minimum value of 2 when $r = \infty$.

The design of the coupling transformers, T_1, T_2, T_3 and T_4, depends on the factors mentioned in Section 2. For example, with transformer T_4, which feeds the negative-sequence starting arrangement, if the impedance reflected by the primary winding is already chosen as r_f, the mimimum required output voltage for operating the starting circuit is V_0, and for any fault the primary current is given by

$$\frac{i_p R_n + i_r R_n \angle 60°}{r_{ft} + R_n + R_n \angle 60°} = AI_F$$

where r_{ft} is the total reflected impedance across either side of the sequence network.

Therefore the impedance across the secondary winding is $n_4^2 r_f$ and the primary current is xAI_{fl}, where x is the setting for earth faults.

The secondary current is $\frac{xAI_{fl}}{n_4}$

$$V_0 = \frac{xAI_{fl}}{n_4} x n_4^2 r_f = Ar_f x_{fl} I n_4$$

From which
$$n_4 = \frac{V_0}{Ar_f x I_{fl}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

and
$$R_4 = n_4^2 r_f = \frac{V_0^2}{A^2 r_f x^2 I_{fl}^2} \quad . \quad . \quad . \quad . \quad (16)$$

The same procedure can be followed in the design of the other transformers.

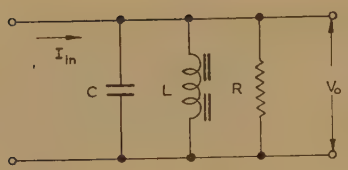
(9.3) Effect of D.C. Asymmetry on the Performance of the Phase-Comparison System

As discussed previously, the positive half-cycle is used for local tripping, whilst the negative half-cycle is used for transmission of blocking carrier. By reference to Figs. 16(*c*) and (*d*) it can be seen that the negative d.c. transient will reduce the duration of the normally positive half-cycle by the angles θ and ψ, while the positive d.c. transient will increase it by the angles θ and ψ. The reduced angles (effect of negative d.c. transient) will be considered positive, and the increased angles (effect of positive d.c. transient) will be considered negative. This effect of d.c. transient tends to change the angle of stability of the relaying system by an angle equal to the sum of θ_1, ψ_1, θ_2 and ψ_2. This can be positive, zero or negative, in which cases the angle of stability will be increased, unaffected or reduced, respectively.

For external faults, the fault currents are approximately the same at both ends of the line, and owing to the phase reversal of the current transformers at one end, the d.c. offset, if positive at end 1, will be negative at end 2, and vice versa. Consequently, the sum of θ_1, ψ_1, θ_2, and ψ_2 will be zero or very small, and the angle of stability will be unaffected irrespective of any d.c. offset in the fault current.

For internal faults the d.c. offsets at the two ends of the line may be independent of different magnitudes and polarity. The worst condition is when the d.c. offsets at both ends are negative, in which case θ_1, ψ_1, θ_2 and ψ_2 are all positive, and the angle of stability may be increased to such an extent that it causes delay in operation for one complete cycle. These effects, for external and internal faults, are illustrated in Figs. 17(*a*) and (*b*).

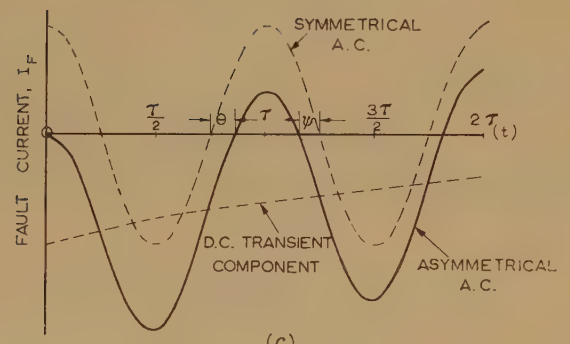
Fig. 16(*d*) shows a simple graphical way for finding θ and ψ for any d.c. offset magnitude and time-constant. A cosine wave is drawn on a linear-log scale; the intersections of the straight line representing direct current with alternate half-cycles give θ



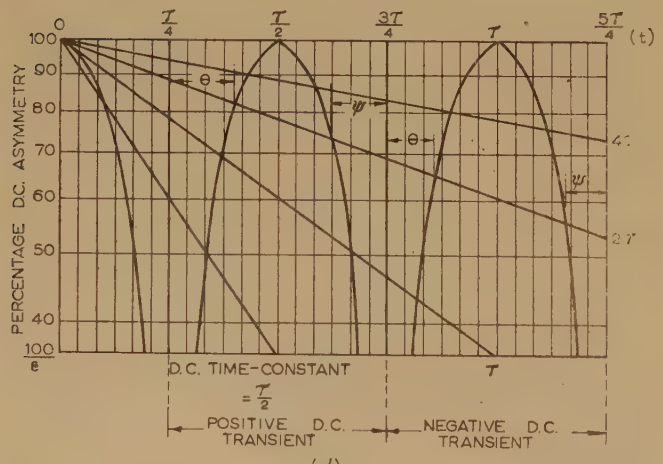
(a)



(b)



(c)



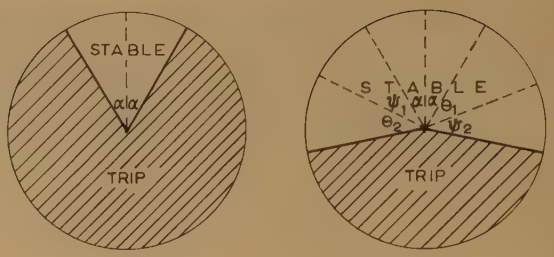
(d)

Fig. 16.—Transient analysis.

(*a*) D.C. transient filter.
(*b*) Performance of d.c. filter.
(*c*) and (*d*) Analysis of performance with d.c. transient.

and ψ for negative d.c. offset, while its intersections with the other half-cycles give θ' and ψ' for positive d.c. offset. It is sufficient to draw the first one or two cycles of the cosine wave where the effect of the direct current is more pronounced.

It has been demonstrated that the relaying system is inherently stable against d.c. offset in the fault current. The worst effect that may result in the case of internal faults is that the time of operation may be delayed for one complete cycle. However,



(a) (b)

Fig. 17.—Effect of d.c. transient on the angle of stability.

(*a*) Polar representation of the stable and tripping zones for external fault with or without d.c. offset and internal fault without d.c. offset.
(*b*) As for (*a*), but internal fault with negative d.c. offset.

since the relaying system is intended for fast operation, such a probability of time delay may be undesirable, and the d.c. transient should be eliminated by a filter network.

The filter network [Fig. 16(*a*)] comprises a parallel *LC* circuit tuned to the power frequency and in parallel with a resistance *R*. If the current fed to this circuit has a 100% d.c. offset,

$$i = I(\cos \omega t - \varepsilon^{-t/\tau})$$

where: ω = Power angular velocity.
τ = Time-constant of the d.c. component.

For the network,

$$z_p = \frac{LRP}{LCRp^2 + LP + R}$$

Considering the a.c. component of the input current,

$$i = I \cos \omega t$$

$$i_p = \frac{IP}{P^2 + \omega^2}$$

$$V_p = i_p z_p = \frac{I}{C} \frac{P^2}{(P^2 + \omega^2)[(P + \alpha)^2 + \beta^2]} \quad . \quad . \quad (17a)$$

where

$$\alpha = \frac{1}{2CR} \quad \beta = \frac{1}{2}\sqrt{\left(\frac{4}{LC} - \frac{1}{CR^2}\right)} \text{ and } \alpha^2 + \beta^2 = \omega^2 = \frac{1}{LC}$$

The condition for eqn. (17*a*) is $R > \frac{1}{2}\sqrt{L/C}$,

whence $$V_t = \frac{I}{C}\left[-\frac{1}{2\alpha}\cos \omega t + \frac{\omega}{2\beta\alpha}\varepsilon^{-\alpha t}\sin(\beta t + \psi)\right] \quad . \quad (17b)$$

$$\psi = \arctan \frac{2\alpha\beta}{\beta^2 - \alpha^2} + \arctan \frac{\beta}{\alpha}$$

Considering the d.c. component of the input current,

$$i = I\varepsilon^{-t/\tau} = I\varepsilon^{-\gamma t}$$

$$i_p = \frac{I}{P + \gamma}$$

$$V_p = i_p z_p = \frac{I}{C} \frac{P}{(P + \gamma)[(P + \alpha)^2 + \beta^2]} \quad . \quad . \quad (18a)$$

whence

$$V_t = \frac{I}{C}\left(\frac{-\gamma}{\omega^2}\varepsilon^{-\gamma t} + \frac{1}{\beta}\varepsilon^{-\alpha t}\sin \beta t\right)(\alpha^2 + \beta^2 = \omega^2) \quad . \quad (18b)$$

Adding eqns. (17*b*) and (18*b*),

$$V_0 = -\frac{I}{C}\left\{\frac{1}{2\alpha}\cos\omega t - \frac{\gamma}{\omega^2}\varepsilon^{-\gamma t} - \varepsilon^{-\alpha t}\left[\frac{\omega}{2\beta\alpha}\sin(\beta t + \psi) - \frac{1}{\beta}\sin\beta t\right]\right\} \quad . \quad (19)$$

The last term in eqn. (19) represents the parasitic oscillations that decay with a time-constant, $1/\alpha$, which is very small (usually less than a half-cycle) and can therefore be neglected. The ratio of the d.c. to the a.c. component in the output voltage will be $2\alpha\gamma/\omega^2$ for 100% offset in the input current.

In the experimental circuit,

$$L = 1 \text{ henry}$$

$$C = 10\,\mu\text{F}$$

$$R = 400 \text{ ohms}$$

$$\alpha = \frac{1}{2CR} = 125$$

The time-constant of parasitic oscillations is

$$\frac{1}{\alpha} = \frac{1}{125} = 8 \text{ millisec}$$

which is less than a half-cycle, and the ratio of the d.c. to the a.c. component is

$$\frac{2\alpha\gamma}{\omega^2} = 25{\cdot}5 \times 10^{-3}\gamma \text{ (on a 50 c/s basis)}$$

For $\gamma = 10$, i.e. when the d.c. time-constant is 5 cycles, the ratio is 2·55%.

For 100% offset in the input current, the d.c. component in the output voltage will be 2·55%, and less for a longer time-constant.

Any nth harmonic in the input current will also be attenuated in the output voltage by a factor

$$\frac{2\alpha n}{\sqrt{[(n^2-1)^2\omega^2 + 4n^2\alpha^2]}}$$

This factor is less than unity, and diverges quickly for higher harmonics.

DISCUSSION ON

'POWER SYSTEM PROTECTION, WITH PARTICULAR REFERENCE TO THE APPLICATION OF JUNCTION TRANSISTORS TO DISTANCE RELAYS'*

AND

'A DUAL-COMPARATOR MHO-TYPE DISTANCE RELAY UTILIZING TRANSISTORS'†

Before the North Midland Centre *at* Leeds *7th January, and the* North-Western Measurement and Control Group *at* Manchester *21st January*, 1958.

Mr. W. J. A. Painter (*at Leeds*): The authors state that they have proved the reliability of transistors by ageing tests. Are they satisfied that the transistors can fulfil the requirements of protective equipment by instant operation after a long period of quiescence, and that the properties of the transistor or its components are not affected adversely under these conditions. Will the transistor require to be 'energized' at periodic intervals to retain its characteristics?

The authors state that they have made progress towards simplifying the transistor relay. To what extent, for example, has the relay shown in Fig. 6 of Paper 2177 S been simplified?

Can the transistor relay be tested and repaired as necessary in the field or does it need test-room treatment? At what interval does a transistor require to be tested? Are simple tests sufficient to prove the 'goodness' of a transistor, or is it necessary to reproduce the family of curves shown in Fig. 1(*c*) of Paper 2085 S?

Is it necessary to take special precautions during test against excessive or reversed voltages, or during handling against vibration or shock?

Has development since the publication of these papers progressed sufficiently to enable the authors to state an economic case for, or against, transistor relays?

Mr. E. C. Smith (*at Manchester*): The authors have carried out their research in a laboratory under ideal conditions of cleanliness, temperature and humidity, but it may not be like that on site, and it is there that protective-gear maloperations occur.

Experience shows the causes of maloperation to be mainly non-technical—things like broken fuses, high-resistance contacts and open-circuited coils, and yet those schemes still work in theory even though not on site. This appears to be an argument in favour of transistorized protection with no moving parts, but it is not. We have introduced other hazards. For example, transistorized protection uses small currents and voltages, and the behaviour of the equipment is dependent on the accuracy of those quantities. Thus voltage pick-up on the wiring cannot be tolerated, but it may occur under fault conditions. There is the problem of voltage control of the batteries, since it is presumably desirable to eliminate charger ripple, and there is the hazard of component failure and the varying resistance of joints. It is one thing to 'tailor-make' a set of protection for laboratory tests and quite another to use components which have been made and assembled in thousands. This latter point is always a risk, but it may be more so when using such small currents and voltages.

The authors envisage that the operating times of three half-cycles will be reduced. There is already much high-speed protection in service on which maloperations sometimes occur because of transient conditions, and yet we are trying to go even faster. Although we must always be ready to entertain new ideas, we must be sure that we are not gaining in speed and sacrificing reliability.

As there are no restrictions on the currents and voltages available for use with distance protection, why have the authors selected this for their first experiment? Why not start research on pilot protection, where design difficulties are experienced because of the necessity to keep within imposed limits of voltage and current on the pilots?

In conclusion, I would ask the authors not to look upon protective gear as a group of relays on a bench in a laboratory, but to look upon it from the point of view of the engineer who is called from his bed at three o'clock in the morning to attend to a fault on the protective gear; from the point of view of the engineer who has to answer for a maloperation; and from the point of view of those thousands of people who may, for a time, be unnecessarily deprived of light and power.

Mr. G. Fielding (*at Manchester*): Associated with the development of modern high-speed schemes is the increasing problem of fault location. A distance scheme offers the ideal apparatus for the development of such a technique. It seems unfortunate, therefore, that any improvement in speed and accuracy of relay response has not associated with it some method of recording the location of fault.

The reach of the 'mho' relay is affected by the presence of arc resistance, and while some reduction in zone 1 is permissible, zone 2 must extend beyond the next busbars. There is therefore a minimum acceptable distance between relaying points for any particular fault level and system voltage.

The time delay necessary between zones must be related to the maximum effect of circuit Q-factor and must include a margin for circuit-breaker clearance time plus an amount for errors. Accelerated tripping would therefore appear necessary for section faults beyond zone 1, and suitable channels would be required.

Voltage-regulation limits must be imposed on the d.c. power supplies, and a specification of permissible ripple content is desirable. To meet the power-supply standards of the laboratory proves difficult under site conditions.

The miniaturization of relay panel components will result in a change in the technique of panel design and wiring. Avoidance of open loops and the use of screened cables are necessary because of higher input sensitivities. Centralization of controls, indications and relays will permit supervision of large stations from one control point. These possibilities are of greater relevance with the introduction of nuclear power stations.

Polarization of the relay elements from adjacent phases has advantages over the use of 'memory'. The faults for which memory is most required cause the greatest time delay in relay operation owing to the high plant/line ratio for close-up faults. The extension of memory by the adjustment of the Q-factor of

* Adamson, C., and Wedepohl, L. M.: Paper No. 2085 S, August, 1956 (see 103 A, p. 379).

† Adamson, C., and Wedepohl, L. M.: Paper No. 2177 S, September, 1956 (see 103 A, p. 509).

the tuned circuit must be limited, however, since it results in rotation of the mho-circle diameter.

The authors' reference to 120 miles as a suitable limit of line length for phase-comparison carrier protection is misleading. The matter is one of technique rather than principle, and, in fact, much greater lengths of line can be protected over high-frequency channels.

Mr. H. G. Bonson (*at Manchester*): Distance-protection schemes in general suffer from the following weaknesses:

(i) Failure to operate on near faults because of the lack of polarizing voltage. This is partly overcome in the present case by 'memory action', but since this depends upon delaying the collapse of the relay voltage until after the fault current has begun to flow, it seems probable that the corresponding delay occurring on voltage recovery might occasionally lead to maloperation.

(ii) The necessity for time delay, either fixed or of an automatically controlled nature, to prevent transient overreach. The dual-comparator system provides the second arrangement at the cost of duplication of much equipment.

(iii) The difficulty of maintaining accuracy of measurement over a wide range particularly at the lower voltages. The solution to the bias problem afforded by the compensating circuit (see Fig. 4 of Paper No. 2177 S) is attractive, and a similar system deriving a compensating voltage (perhaps from the current circuits) could be applied to rectifier-operated distance relays to compensate for the voltage drop of the voltage-circuit rectifiers.

(iv) The relatively large amount of equipment required for full 3-zone 3-step protection. Have the possibilities of transistors as high-speed switching devices been fully explored with a view to reducing this amount?

In conclusion, I have two queries regarding the system of plotting relay characteristics on the accuracy/range curves (e.g. Fig. 8 of Paper No. 2177 S):

Why does the range scale begin at unity? Surely it is possible for applications to exist in which the source impedance is smaller than that for which a given relay is set.

Cannot a better name be found for the 'accuracy' scale? The present one seems meaningless as applied to the curves for constant time of operation, although highly appropriate to the threshold-of-operation curve.

Mr. F. H. Barratt (*at Manchester*): The use of a dual comparator for eliminating the transient overreach effect is very satisfactory in preventing false tripping, but it produces severe delay under certain conditions. For example, in the waveforms shown there would be a 6-cycle delay if the relay setting had been for a slightly shorter distance. The authors have mentioned the possibility of filtering the d.c. transient between the voltage transformer and the comparator. It would be interesting to know whether they have considered means of cross-connecting the two comparators in such a way that a mean is taken between the integration peaks on the two sides. In this way, the distance measurement should be determined in the first cycle.

A practical point in Paper No. 2177 S is the peak value of the voltages V_1 and V_2. The paper suggests that it may be about 200 volts. Is this not excessive for the majority of transistors, even when applied through a 10-kilohm resistor?

Messrs. C. Adamson and **L. M. Wedepohl** (*in reply*): In reply to Mr. Painter, we have not conclusively proved the reliability of transistors by ageing tests. Tests thus far conducted have merely been very encouraging. An 'on site' testing programme is being arranged to determine the reliability after long periods of quiescence. There will be no need to energize the relays periodically to retain their characteristics.

Relays have been considerably simplified. No direct comparison can be made with the relay shown in Fig. 6 of Paper No. 2177 S, since further modifications have been made to basic operating principles. However, it has been possible to devise relays using from three to nine transistors with far greater consistency in speed of operation over the relay mentioned above. For the greatest speed of operation and most robust slave relay units, indications are that four to six transistors will be required in each relay.

A small selenium diode is usually used to limit the maximum reverse voltage to approximately 0·5 volt. No information is available on shock resistance. The indications are that transistors are less sensitive to shock than thermionic valves, which have been used successfully in protective-gear carrier equipment.

In reply to Mr. Smith, we are in full agreement about the importance of testing new equipment under the most arduous conditions before drawing final conclusions as to their merits. So far, a very intensive series of laboratory tests has been successfully completed, and it is hoped to complement the test data with information obtained from a complete terminal installed in South Africa.

While the transistorized equipment does operate at very low power levels, it must be emphasized that the relay accuracy is determined by the accuracy of the replica circuits, and is exactly the same problem as in more conventional distance relays. The transistors are used as functional switches, and are consequently not highly sensitive to battery regulation and hence ripple. In a recent test a reduction of 20% in battery voltage showed a reduction in reach of 5% for a fairly large range factor. This was not due to any decrease in accuracy of replica circuits but to a reduction in efficacy of the bias compensating network.

In most cases, a speed of three half-cycles would be more than adequate, but there are special cases where a speed of one cycle has been found necessary to maintain system stability. In such cases, electronic relays which maintain their speed of operation at greatly reduced power levels are at an advantage over conventional relays.

There are no restrictions on currents and voltages available for protection. The two papers describing transistorized distance relays show results arising out of a general project investigating the suitability of transistors in protective gear. Other research is being carried out in other forms of protection, including pilot wires.

Finally, we have attempted to view the project from the point of view of the system engineer. For this reason it was deemed necessary to obtain 'on site' information and not to rely entirely on the results of laboratory tests.

In reply to Mr. Fielding, we have not considered the problem of fault location in any detail. It may be possible to adapt the equipment to measure distance, but this would require continuous energization of the faulted line. Greater accuracy is probably attainable by using radar techniques for fault location.

The problem of arc resistance is common to distance protection of all types. Reactance relays could be used, but they do not, in all cases, provide an acceptable solution.

The time delay encountered in the presence of d.c. components at large range factors has been eliminated in improved relays, so that fast tripping times occur at all points within the operating plane of the relay. However, the problem of zone 2 time delay at the end of a feeder remains, and an important feeder would have to be removed by the use of a carrier link.

Voltage regulation has already been mentioned. It is unlikely that the limits required would be severe.

Site tests will provide information on susceptibility to pick up on stray loops. The problem will, in all probability, be far less severe than in a high-impedance thermionic-valve-type relay, because transistors are current operated and consequently have a very low input impedance. However, the problem has been taken into account by avoiding large-area loops and further by mounting equipment and cables in an earthed telecommunication-type rack. This should provide shielding against stray fields.

Unfaulted phase polarization is suitable for all faults, other than 3-phase, in which case 'memory' is a solution. Rotation of the 'mho' circle due to frequency change has been greatly reduced by using tuned circuits with time-constants of the order of 10–14 millisec.

In reply to Mr. Benson, 'memory' has already been mentioned in our reply to Mr. Fielding. We agree that the use of tuned circuits does introduce new hazards. However, by reducing the time-constant to 14 millisec or less, the possibility of false operation is so small as to be negligible. The polarizing-voltage delay during voltage recovery has been examined analytically and experimentally, and with short time-constants it does not cause maloperation. Time delay, to avoid transient overreach, is now unnecessary. In the latest relay types, operating principles have been modified, and speed of operation as well as accuracy are independent of d.c. components.

Compensation does extend the useful range of relays. It should be noted that simplifications have been made to the compensating circuits.

The possibility of using switched schemes has been considered. It is unlikely that they would be competitive with conventional equipment, because speed of operation and range are not at a premium in such applications. Consequently, very cheap conventional schemes are possible. It is unlikely that supply engineers would consider the use of a high-speed switched distance relay terminal to protect an important high-voltage feeder.

The range curves begin at unity merely because the performance of the relays does not show any variation for lower ranges. Had it been necessary, the wire could be started at a lower range. Finally, both the terms 'accuracy' and 'range' have been the subject for discussion, and more appropriate names will be considered.

In reply to Mr. Barratt, improved relays have made use of the average effect in the two push-pull comparators. In this way, transient time delay has been eliminated, operating times of one cycle at all times have been achieved, and, in addition, circuit simplification has been possible.

The peak value of 200 volts on the relay is possible, owing to the fact that a transistor is current-operated. A small selenium diode in shunt with the base-emitted junction provides a low-impedance path to positive signals while the junction itself offers a low impedance to negative signals. Thus one need only consider the input current, which is almost completely determined by the input resistance; for example, taking the average base-emitter voltage as 0·5 volt, the r.m.s. power at 200 volts (peak) is

$$\frac{200}{\sqrt{2}} \times \frac{1}{10\,000} \times 0{\cdot}5 \times 1\,000 = 7\,\text{mW}$$

Only half this power (3½ mW) is dissipated in the transistor, the remainder being consumed in the protecting selenium diode. This is only a small fraction of the permissible power in the smallest transistors, and presents no problem.

DISCUSSION ON 'BRITISH COLUMBIA–VANCOUVER ISLAND 138 kV SUBMARINE POWER CABLE'*

Before the North-Eastern Centre *at* Newcastle upon Tyne 28*th October*, *the* North-Western Centre *at* Manchester 5*th November*, *the* South-West Scotland Sub-Centre *at* Glasgow 12*th November*, *the* North Staffordshire Sub-Centre *at* Stone 18*th November*, *the* Western Centre *at* Cardiff 9*th December*, 1957, *the* Mersey and North Wales Centre *at* Liverpool 6*th January*, *the* South Midland Supply and Utilization Group *at* Birmingham 10*th February*, *and the* Southern Centre *at* Brighton 19*th March*, 1958.

Mr. A. E. Bishop (*at Newcastle upon Tyne*): I would like first to deal with economic questions. What relative proportions of the total cost were absorbed by the cable and by the installation? Installation looms so large that I wondered whether the cable was just an adjunct to the scheme. The maximum electric stress is 85 kV/cm, which is rather low by modern standards, although engineering caution may have dictated it. Would a cheaper cable, such as a 100 kV/cm one, result in a reasonable economy? This does depend on the ratio of cable cost to installation cost, and the fact that the capacitance currents would increase; these already reduce the current rating by 6%.

With regard to current rating, I should like to know how the thermal resistivity of the sea bed was determined. I am particularly interested in the matter in view of an American account a few years ago of the overheating of river-crossing cables owing to the very high thermal resistance of the river bed. The current rating of 98% of the cable is determined by the 2% which is out of the water. Thus 12–13% of the rating is lost. This is not economic, and could have been avoided by jointing short lengths at each landing position.

Nothing has been said on possible alternative types of cable for this crossing. Although the pre-impregnated cable is, at present, the only type of cable which can be manufactured in continuous lengths, factory jointing of excellent quality has been claimed by Bertaux† for mass-impregnated cables. Furthermore, what is the possibility of using non-draining gas-pressure cables not of the pre-impregnated type? For some reason, non-draining cables appear to be limited to 11 kV or possibly 33 kV. Is this inherent or can they be developed to higher voltage?

With regard to installation, was any final examination made, by diver or television camera, particularly about the rock ridge before Galiano Island? What are the authors' views on specially-designed cable ships? We appear to lack information also on the low pressure at which the alarm is given and the time the gas took to pass through the cable from end to end.

On accessories, I am surprised to see a separate sealing end for gas feed. Also, I presume that the rigid joints were checked for gas tightness by the vacuum technique. Why are Monel metal and aluminium alloy used for sleeve materials? At what voltage did the factory joint break down?

The capacity of the Jordan River plant is given in Table 1 as 26·4 MW, and in Fig. 1 as 27·1 MW. This is not a great difference, but with generating capacity, every little helps.

* Ingledow, T., Fairfield, R. M., Davey, E. L., Brazier, K. S., and Gibson, J. N.: Paper No. 2354 S, April, 1957 (see 104 A, p. 485).

† C.I.G.R.É., Paris, 1954, Paper No. 220.

Mr. G. P. Cundall (*at Newcastle upon Tyne*): The enterprise described in the paper has been the combined achievement of production, mechanical and civil engineers, as well as electrical engineers. Its successful conclusion is a tribute to the organization on a grand scale by those in charge. Were the manufacturing and contracting organizations given complete responsibility for the design, planning and execution of the work, and if so, would the authors state what duties were fulfilled by consulting engineers?

The estimated cost per kilowatt-hour of steam-generated power in a power station on Vancouver Island is given, but, although the transmission cost of hydro-electric power is given for the submarine-cable route, its total cost is not. It would be interesting to know what this amounted to and also the expected life of the cables, which must have been assessed in order to arrive at the estimate.

The use of steel-wire armoured single-core cable is contrary to normal land practice, and one would expect that it could have been avoided if aluminium sheathing had been used. It would be interesting to know whether aluminium sheaths were not adopted because of manufacturing or handling difficulties.

The joint illustrated in Fig. 7 was evidently made in 24 hours, which compares favourably with the length of time normally taken to complete a gas-pressure cable joint. Could the authors say whether it was pneumatically tested before being lowered into the sea?

In the Appendix the reactance of the cable is shown to be less for spacings of 500 yd than for 250 yd. This is surprising, and it would be interesting to know how the reactance was calculated and whether it has since been measured. Would the authors also state why such wide spacings were adopted?

Mr. J. Queen (*at Newcastle upon Tyne*): I am particularly interested in the protection and fault-clearance aspects, and would like to know the 'zero-sequence impedance' per mile of the 3-cable 3-phase link; what earthing arrangements are provided for the protection of the link cables, and what maximum earth-fault current is anticipated in the submarine cable link and under what conditions will it exist?

Are these cables used for part of a telephone communication system as well as for power transmission, and, if so, could an outline of the scheme be given?

During manufacture of these cables there appears to be a possibility of a seam being formed in the lead sheath during the extrusion process, or alternatively, a possibility of burning the paper insulation of the cable when the speed of the press is varied. Can the authors state how these defects were avoided?

The method of repairing the cables is most interesting, and it would be much appreciated if the authors could explain, first, how the air content and gas humidity are checked before a cable joint is sealed; secondly, how the force of explosive is concentrated on the cable for cutting purposes without damage to the grapnel after the cable fault has been located; and thirdly, how these cables are dried out during cable fault-clearance operations.

Mr. J. E. Peters (*at Manchester*): The supply position on Vancouver Island is set out in Sections 2 and 3 of the paper, but, having regard to the magnitude of the existing load, it seems a little unusual that the additional power requirements of 120 MW should be supplied over a single 3-phase circuit, even allowing for the fact that a spare phase could be brought into circuit rapidly by remote switching. In the event of this circuit failing at a time of peak load, it would appear that considerable load shedding would be necessary in order to maintain frequency and permit the re-energized circuit from the mainland to be resynchronized. This leads me to my next question. Why were five cables provided? I should have thought that the saving in losses by running two 3-phase circuits normally in parallel would have gone a long way towards paying for the sixth cable, whilst, on the score of security of supply, other powerful arguments could have been used.

Long cable runs at this voltage always bring with them problems due to the heavy charging currents taken by the cables (in this case, approximately 175 amp per phase). It would be interesting to know whether any such problems have arisen on the B.C.E. Co. system, particularly at times of light load.

With regard to the design of the cable, I was interested to note that galvanized-iron armouring had been selected because of its resistance to abrasion, in spite of the high losses entailed. I assume that the jute serving over the armour is regarded as ineffective once the cable has been laid and that the armour has to withstand both abrasion and corrosion owing to direct contact with the sea water. The authors' comments on this point would be of interest. Would they also comment on the reversed-lay sections of insulating papers both from the mechanical and electrical design points of view?

At present, interest is focused on the proposed cross-Channel cable, and the experience gained on the Vancouver Island project will be of immense value in solving the problems of interconnecting the British and French supply systems. If the technical problems of high-voltage d.c./a.c. conversion can be solved economically, the future is full of interesting possibilities for high-voltage submarine power cables in many parts of the world. In our own immediate locality it is interesting to note that Northern Ireland is less than 25 miles from the Scottish coast, and the Isle of Man is within sight of the atomic power station at Calder Hall on a clear evening.

Mr. J. Wallace (*at Manchester*): The authors refer to the hazards from shipping, and whilst these have been minimized by selection of the route and the prohibition of trawling by the Department of Fisheries in certain areas, damage to the cables by ships' anchors and the like can ultimately be expected. Should this occur in deep water, a considerable length of cable between two joints would have to be inserted, and I would be interested to know how this extra length would be disposed on the sea bed to avoid any tendency to loop or kink the cable. What happens to the small residual tension with which the cable was originally laid?

Reference was made to the comparative abrasion resistance of aluminium-alloy and galvanized-steel wire armouring. Would the authors state whether bronze armouring was considered with a view to minimizing losses?

Mr. F. Mather (*at Manchester*): Under what circumstances can a voltage of 10 kV appear between the armour and gas-retaining sheath? Presumably they will be bonded and earthed at each end.

In the event of damage to the cable, how long can gas pressure be maintained to prevent ingress of water to the insulation? The method of locating a submerged gas leak is excellent, but it would appear difficult to apply if the cable sustained damage in two places, and the consequence of the cable being cut in the wrong place owing to incorrect fault location would be serious. Has such a condition been considered, or is it felt that it will never occur?

Mr. E. Roscoe (*at Manchester*): Since the cables lie apart on the ocean bed, does the reactance between various cores affect the carrying capacity of the cable appreciably?

What happens to the lead sheaths at each end? Are they left in complete isolation or are they bonded together and earthed at one or both ends? If they are bonded at one end only, is there a dangerous voltage at the other end? If they are bonded at both ends, do the eddy currents in the lead sheath cause circulation of current, and, if so, to what magnitude?

Mr. J. S. Hastie (*at Glasgow*): With regard to Fig. 5, I am

struck by the close resemblance to the conventional oil-filled cable. The only important difference is that, with the oil-filled cable, arrangements external to the cable have to be made to cater for the expansion and contraction of the oil; with the cable described in the paper, since the gas is compressible, it is self-compensating throughout its length, and therefore suitable for installation in long lengths in inaccessible positions, such as on the bed of the ocean.

The cable is of the gas-filled type insulated with pre-impregnated paper tapes applied with graded thickness and tension. It would be interesting to know whether any attempt was made to grade the size and distribution throughout the dielectric of the gas-filled spaces as in the original Beaver–Davey patent.

I note that the paper tapes were applied by means of a cage-type lapper having four sections rotating in opposite directions. I am tempted to ask whether the authors were obliged to adopt reverse lapping with a view to reducing troubles due to torsional stress in the core, and whether they would not have preferred to apply the paper tapes with the same direction of lay throughout, if it had been practicable.

In Section 8.1, I am surprised to see the statement implying that it was safe to leave the cable exposed to the atmosphere for some weeks. I should have thought that the safe period would have been of the order of hours. It is difficult to understand why so much care was taken at the paper-lapping machine to install it in a controlled atmosphere and then to leave the cable exposed to the shop atmosphere on the accumulator. Would it not have been possible to enclose the whole unit and control the atmosphere in contact with the insulation right up to the lead press?

It is understandable that the authors decided to use a reciprocating press which can be stopped for an appreciable time without detriment to the cable. But I am surprised to note the size of press used, i.e. 1000 tons. It would be interesting to know why a larger press was not selected so as to reduce the number of stops for recharging.

I note that the sealing ends are compound filled. No reference is made to any method of maintaining a balance between the gas and oil pressures, but I assume that the gas is in contact with the surface of the compound. With this arrangement some of the gas will be dissolved in the compound, and this may cause difficulty when the cable is depressurized. It would be interesting to know the time required to bring the system down to atmospheric pressure.

Mr. J. T. Henderson (*at Glasgow*): During lead-covering the sheath was extruded carefully on to the insulation to ensure that there was no clearance between lead and insulation. With the reconstituted joint, however, it is necessary to have an oversized lead pipe fitted over the joint; this pipe is then swaged down to the cable sheath at either end and then joined to the cable sheath by means of lead burning. There must be clearance between the insulation and the lead-alloy pipe to enable the pipe to be passed over the insulation. Is this clearance filled in any way?

During storage the bottom turns of cable appear to have a considerable weight bearing on them. Were any difficulties encountered owing to this fact?

The vulcanized-rubber protection was subjected to heat for three minutes. At the end of that time, was the protection fully cured or was the cure only initiated?

The high-voltage interconnection between the United Kingdom and France has been discussed frequently in the technical Press. Its capacity is 160 MW, which is slightly greater than that of the Vancouver cable. With the cross-Channel cable, economy is achieved by having a d.c. link with the possibility of using either a solid paper-insulated cable or a polythene-insulated cable. Was this possibility investigated for the Vancouver Island crossing? It is, of course, appreciated that differences in terminal frequencies and voltages influence the economy of the cross-Channel cable.

Mr. H. Marshall (*at Glasgow*): How frequently was the lead-sheath thickness checked with the γ-ray photographic unit, and what variations, and type of variations, in thickness were discovered? Since it was presumably necessary to alter the thickness during extrusion, was the press fitted with any device for measuring the adjustment, such as is fitted to the German aluminium-cable-sheathing press on which the sheath thickness can easily be changed by advancing or retracting the die by means of a hydraulically-operated ratchet and key?

In view of the difficulties which have been experienced with 'birdcaging' of wire-armoured cables, it would be interesting to know the basis of the experiment which determined the optimum lay of 12 times the pitch-circle diameter.

In Section 6.2 it is stated that the sheath was extruded onto the insulation with a shrinkage of 30–40 mils diametral. Is this a calculated value or was it arrived at by experiment?

Mr. C. C. Pimble (*at Stone*): The paper quotes a cumulative load growth of 10% per annum. Could the authors state what type of load was mainly responsible for this growth?

Would the spare cables be put into service in order to subject them to load cycles, and why were the telephone exchanges used in preference to the supervisory equipment for indicating gas and circuit failures?

In Fig. 6, what was the setting of the arc-gaps in relation to the insulation co-ordination of the system?

Section 12 refers to outages for testing. It would be interesting to know what routine tests, if any, are carried out, whether permanent test arrangements are provided at the terminals, and what provision is made for isolating the cables from the overhead lines.

Mr. R. W. Palmer (*at Stone*): I would like to know why the manufacture of power cable in one long continuous length should have presented any novel problem to the industry, assuming that the individual conductors, tapes or armouring are allowed to be discontinuous at irregular intervals. A second query is on the use of the same type and weight of armouring for the deep-water section as for the shore ends. Telecommunication experience suggests that tidal movement and the risk of dragging anchors in shallow water demand greater mechanical protection than in the deep-sea sections. To press this point even further, has the electricity supply industry considered the British Post Office project to use deep-sea cables whose tensile strength is provided by a central core instead of by external armour, thereby avoiding the problems of kinking when laying cables whose mechanical strength is applied spirally on the outside of the cable?

Mr. D. H. Tompsett (*at Stone*): It is tempting to speculate on the effect this achievement will have on the future development of this part of the B.C.E. Co. system. It seems probable that ultimately, and perhaps earlier than the authors envisaged, the cost of energy from a large nuclear power station will be lower than that for either transmitted hydro-electric energy or local fossil-fuel thermal generation.

If present British practice were followed, a nuclear station would be sited adjacent to the Strait of Georgia, or on one of its branch waterways, and at an appropriate distance from the nearest centres of population. The problem would then become one of transmitting the power from this site to the load. Studying Fig. 1, and indulging in a flight of fancy, one can imagine a nuclear power station located on Galiano Island supplying power both to Vancouver Island and also to the mainland. The ultimate capacity of the cables would allow a total of 240 MW to flow in each direction, with the security of supply associated with two parallel a.c. cable circuits. Considering a 500 MW

station, however, it would appear desirable to increase the firm capacity of the mainland transmission. This purely hypothetical situation enables me to ask the authors what capacity six cables, similar to those described in the paper or specially constructed, might be expected to have if operated as three d.c. circuits. The rating and reliability of the submarine part of the transmission circuit would certainly be increased by this change, but perhaps the overhead-line section would require supplementing.

For such a step to be economic, it would be necessary to show that the cost of the converting equipment was less than that of the additional a.c. circuits required to give equivalent security. The corresponding losses would also need evaluation. However, in view of comments in the paper about the difficulty of finding suitable routes for the crossing, it is possible that no further a.c. cables can be accommodated. This consideration raises the more general issue of transmission routes, both cable and overhead line, in difficult or congested locations. For all such cases, the use of direct current as an alternative to alternating current must now be given serious consideration.

Mr. C. M. New (*at Cardiff*): Reference is made to a novel method of reducing the gas flow to the minimum if a cable is either severed or badly damaged. Should damage occur in the 100-fathom section, there would appear to be a differential of 35 lb/in^2 between the cable pressure and that of the water. What is the minimum differential pressure required to prevent water from entering the cable? At this rate of flow of gas, how long will the installation maintain the position before further cylinders of gas are required?

During the war I was concerned with the Broadwell i.p. cable installation, and the method of gas-leak detection generally used was known as the 'single-deck oxygen sandwich'. It was quite accurate but very slow to carry out. The method mentioned in the paper for comparing the flow rates at each end of the cable should be much quicker, and I should like to know how long it is estimated that it would take to make the gas-leakage location.

The method of grappling and severing the cable is most interesting. Experience on the Isle of Wight cables, however, has shown that, while picking the cable up when first laid is comparatively straightforward by normal survey methods, the position is far from simple after added lengths and joints have been inserted. Grappling the cable is difficult enough, but to grapple it in the right place is almost impossible. Has this problem been given any thought by the authors?

The temperature, humidity and quality control exercised in the manufacture of the cable is one of the main reasons for the success of the scheme and the already proved reliability of the installation. Such control had to be adopted when making cable in continuous lengths, and undoubtedly it has the effect of ultimately giving the customer an even better product than before. However, the one thing which does not appear to have been tested completely until the cable went into service was the lead sheath. I presume that complete faith had to be put in the lead press and careful control of the metal exercised. The authors then had to hope that no case of porosity in the cable sheath occurred. However, their views on this matter would be welcome.

Mr. J. A. Rees (*at Cardiff*): What consideration was given, during the design of a 15-mile continuous length of cable, to problems which could arise from changes of length, owing to temperature changes?

These problems would be mainly associated with stresses induced in the component parts of the cable owing to their different coefficients of thermal expansion. They would presumably be more serious after the cable ends were secured, when no relative movement could take place between, say, the copper conductor and the steel armouring.

Mr. R. W. Steel (*at Cardiff*): The economics of the cross-Channel submarine cable scheme are based on the diversity between the load on the Continent and in Great Britain. In the project described in the paper, the economics are based on the difference between the cost of hydro-electric energy on the mainland and steam-generated energy produced on Vancouver Island. Is there any diversity between the load on the mainland and that on Vancouver Island, and if so, was this taken into account in preparing the scheme, and what proportion of the whole does it amount to?

Mr. L. J. Archer (*at Liverpool*): I am interested to note that, from load studies made several years previously, it was decided that the additional supply would be required in 1956, and that the cables were commissioned on the 25th September of that year. We are not told the date on which the final decision regarding the submarine cable was taken, but it is obvious that this must have been a fairly long-term project and that the decision must have required a certain amount of courage. When long-term decisions of this nature are taken there are occasions when the changing picture during the preparatory stages causes doubts to arise about the correctness of the decision. It is obvious that what may be called a 'point of no return' is reached fairly early in the proceedings, and that a decision once taken must be adhered to. I should be interested to know how close was the agreement between the estimated (and presumably manufactured) lengths of cable and the actual lengths installed.

On learning that three incidents during manufacture required the use of the reconstituted joint and that an accident during laying required the use of a submarine repair joint, my first reaction was disappointment. On further reflection, however, I think that this is a shortsighted view. There is surely some advantage in having these joints tested in service, no matter to what tests they had been put during development.

I should be interested to know the essential difference between the cable described in the paper and the gas-filled cable of Beaver and Davey.

I am sorry that no details are given of the reasons for choosing the pre-impregnated cable. An obvious one is the difficulty of impregnating the completed 16 miles of core, but when one considers the other difficulties which have been overcome in connection with the project, I wonder whether that is the only answer. Another difficulty would obviously be that of compound migration, particularly on the portion of the route adjacent to Galiano Island where gradients approach 1 in 5. There might be no advantage in improving the electric strength because the resultant reduction in thickness would cause an increase in charging current. The charging current already represents some 6% of the total sending-end current.

It would be interesting to know the proportion of the 'sheath, reinforcement and armour' losses, comprising some 46% of the total losses, which is due to the armour. It seems a pity that the idea of using non-ferrous armouring had to be abandoned.

I wonder whether the possibility of increasing the conductor size at the shore ends was considered. Such an idea seems to follow from the lower operating temperatures of the under-water section, which means that the rating is determined by the shore ends, and also from the fact that the sending end (which may perhaps be either end according to operating conditions) has to carry, in addition to the load current, the current to supply all the losses and also the quadrature charging current amounting to 180 amp and resulting in the 6% increase mentioned above.

Finally, I should like to ask whether p.v.c. was considered as an anti-corrosion protection, and, if so, the reason for discarding it.

Mr. H. M. Fricke (*at Birmingham*): I would like to have more information about the rubber sheath which would be required

to withstand, on occasions, a voltage of 10 kV. I assume that the rating of the cable was decided by the shore ends. Why were the shore ends not floated ashore on empty drums, and why was the continuous-extrusion type of lead press not used?

Mr. L. L. Tolley (*at Birmingham*): The cable is built up with a core and insulation and then a lead sheath, which is the water barrier. I remember that when, some 30 years ago, we laid a telephone cable across the Straits of Dover, with paper core and lead sheath, it gave a lot of trouble. I was able to examine sections of the sheath, and it was clear that it had failed from normal fatigue. It seemed that the cable had been looped across the little valleys of the sea bed, and as a considerable tide runs in the Straits of Dover it had swung to and from and fatigued. I notice in the paper that, although in the Vancouver Island strait there was a tidal current, the bottom current was not very high, i.e. about 1 knot, and it may be that no trouble would arise, but I would like to know whether there has been any indication.

My next point relates to the gas pressure in the cable. If the lead sheath were cracked the gas would have to flow from the spiral duct through the paper insulation, and even after it had passed through the crack, there would still be the rubber tape over the sheath. Would the rate of flow be sufficient to indicate with certainty that there was a crack in the sheath? It is mentioned in the paper that the gas supply to the spiral duct is so arranged that, if there were a serious failure, it would provide enough gas to prevent water running up the cable. In the case of a cracked sheath—not a fractured cable—when the gas has to pass through the paper insulation, can an estimate be made of how far the water would spread in from the outside despite being opposed by the pressure of the gas from the inside?

In the event of a repair requiring the services of a cable-laying ship, where is the nearest cable ship to Vancouver Island which could cope with this cable? Alternatively will an adapted scow be used instead of a cable ship?

Mr. H. S. Davidson (*at Birmingham*): This is the first time a pressure cable has been used in an undertaking of this kind, and I think that it is about the third-longest length of submarine power cable that has been laid. In the past, experience of submarine cables has been gained mainly on telegraph cables. Of the damage caused to such cables in the English Channel, some 50% of the faults have been caused by shipping, anchors, trawls and the like. I suppose it is too early to know what is likely to happen to the cables described in the paper. It will be of interest to see whether they do suffer in this way, as the authors mention that there is a considerable amount of shipping traffic in the Strait of Georgia.

With reference to the method of dealing with the cable after a fault has been located, I feel quite apprehensive about the cable being cut by means of an explosive charge, and reliance being placed on the gas pressure to prevent water from entering the cable. I presume that there could be a leakage of gas for some time, and that very special precautions must be taken to ensure that the gas supply cannot fail. I should like to know what these precautions are and how the danger of exposing the cables to water is completely eliminated. The time taken to make a joint after the recovery of a faulty cable is given as about 24 hours, but, in the experimental work done on the cross-Channel cables, a time of 8 hours was considered to be desirable and possible.

Mr. G. S. Buckingham (*at Birmingham*): This great achievement can be regarded as the successful outcome of the merging of two great cable-making companies. One recognizes the practice of using pre-impregnated paper insulation—it would, of course, be impossible to impregnate such very long lengths of cable after insulation—and the use of short-lay reinforcement with wide bronze tapes. (The use of separate longitudinal and circumferential tapes on gas-pressure cables has given trouble and the authors' comments on this decision would be valued.)

We are all interested to know how underwater faults can be repaired on these cables. We are bound to ask such questions, as our own experience makes us aware that cables do get damaged.

It is clear that the authors are prepared for any emergency. The spare cables should provide time for repairs to be made even when bad weather delays progress. It is also clear that they have done everything that skilful design and precision engineering can do to protect the cables from internal or external damage. I notice that this also includes galvanized-steel wire in place of aluminium-wire armouring, although the resulting losses are much greater.

Mr. J. H. Addenbrooke (*at Birmingham*): Are these cable routes marked on navigational charts, because I notice that the cables are laid in both Canadian and United States waters? I take it that the problem of laying cables is more difficult if one does not have local control of the waters, such as when laying cables in the English Channel.

Mr. A. Shaw (*at Birmingham*): It is most unusual to have single-core power cables armoured by the use of steel wires. The electrical losses must be considerable, and, of course, they are present during the whole life of the cable. Could the authors give some idea of the losses on these 120 MW cables?

As no gas cylinders seem to have been attached to the cable ends during shipping and laying operations, what pressure, if any, was maintained in them? If there was no pressure inside the cables, was there not a danger of losing a considerable length owing to the ingress of water, in the event of accidental damage to the lead sheath? It would be interesting to know how long it took to gas 14·7 miles of cable after completion. The use of pre-impregnated paper insulation would, no doubt, prevent the usual compound blockages encountered with conventional gas-pressure cables.

Although the cable was manufactured in complete lengths, the individual strands of copper and steel would have had to be jointed as bobbins on the machine becoming empty. What methods were used to joint the copper and also the steel strands?

Mr. R. A. York (*at Birmingham*): It is interesting that use is not made of longitudinal reinforcing tapes in the cable. In the Midlands we have experienced a number of gas leaks in impregnated pressure cables owing to the longitudinal tapes becoming buckled and the lead penetrated. The different type of reinforcement used on this cable, and the fact that it was not gassed until it was laid, may show the way to a solution of the trouble we have experienced, since, at present, it is not known whether the cause was the locking of reinforcing tapes.

It seems unusual that two spare cables were needed for a single 3-phase circuit, but only one for two 3-phase circuits. This indicates that, since the laying of the first circuit, greater confidence has been gained in the installation.

Mr. G. F. Peirson (*at Birmingham*): The authors state that it had been decided that the cable should not be pressurized before transit, so that it would remain flexible for laying. Therefore, is any difficulty anticipated should the need arise to recover the cable in order to repair a fault? I have in mind the possibility of the cable being relatively rigid owing to the expansion of the lead sheath within the armouring, which was rather more than hinted at in the paper.

Mr. W. Holttum (*at Brighton*): The pattern for future long submarine links may be taken as being set by the use of the gas-pressure type of cable, which can be regarded as the only practicable one for such work. The attraction of the more homogeneous insulation of the oil-filled cable is nullified by the

difficulty, probably insurmountable, of dealing with oil expansion and flow under both operating and repair conditions, and the gas-pressure type seems likely to receive a boost from its use in this case.

A notable feature of the undertaking is the extensive sea-installation trials carried out. The paper refers to the constructional details of the cable design which emerged, and it would be of value if the authors would state fully just what influence the sea trials had on the cable design and also on the method of installation, which could not otherwise be foreseen. A very interesting feature of the cable is the opposing of the twisting forces of the reinforcing tapes and the armour wires in order to minimize the tendency to throw a kink, although apparently the tendency was not positively eliminated in view of the statement in Section 9.3.3 that it was decided to lay with a residual tension. The use of double-wire armour should give more definite stability than the opposing of the torques of two quite dissimilar components of the cable. Coiling down could be provided for by leaving room for tightening between the wires of the inner layer. While this would probably result in the use of thinner wires to keep down the quantity of material, experience suggests that the risk of corrosion can be disregarded, and any reduced resistance to abrasion might be tolerated for the sake of positive elimination of the twisting tendency. The authors' views on this matter would be of great value.

The decision to make a land trial of the scow method of laying to the shores, no actual scow being available, is a little difficult to understand since the real issue would be the behaviour in sea conditions and not verification of the principle.

Fig. 6 shows that an additional sealing-end insulator was used at each termination in order to provide for insulating the gas connection. Why was the usual construction of an insulating pipe inside the sealing-end insulator, as for a cable with no gas duct thus enabling connection to be made to the gland, not used?

With regard to the Tsawwassen termination, would the authors state the gradient in the tunnel, the spacing of the cable racks, and whether the cables are clamped in each rack?

Mr. L. H. Fuller (*at Brighton*): I think that a Table showing the total estimated costs of the alternative projects would have been instructive. I wonder whether consideration was given to the availability of reinforcement from the Bonneville Power Administration network (using perhaps the B.C.E. Co. system power) over the collection of American islands on the same parallel as the Brentwood Bay station. These islands seem to be separated by comparatively narrow channels, although I appreciate that at least one will be a main shipping track. In connection with these shipping tracks, was any interference experienced during the laying operations or did the local fishermen keep clear? I remember Signor Bianca saying that they had great difficulty with local craft during the construction of the Sicily crossing, which was admittedly overhead.

It is interesting to see the use made of the cable during the first four months of operation, and I should like to know the reason for the considerable reduction in load factor during the months of November and December.

I assume that the spacing of 500 yd in the Strait of Georgia was chosen to minimize ships' anchors fouling more than one cable at any one time, noting that 250 yd spacing is used in the Trincomali channel.

The very exceptional measures rightly taken during the manufacturing stage will ultimately prove of benefit to ordinary cable, which, as we all know, sometimes suffers from difficulties ascribed to indifferent, or lack of, supervision at some stage or other.

Mr. J. L. Harland (*at Brighton*): I was present at the trials carried out off Dover in 1953, and my strongest recollection is of the practical difficulties which were encountered. For instance, it might not be appreciated that, when making a joint on the deck of a cable ship, the ship riding at anchor will turn through 180° when the tide changes. Moreover, if matters are not well arranged, the next tidal change may result in a further turn of 180° being applied to the cable ends emerging from the water instead of the removal of the original rotation.

No doubt the authors considered the type of damage to a submarine cable which could be caused by a dragging anchor, and I wonder whether the situation could arise where the cable had parted except for the central spiral steel duct. In this case, would it be possible for the duct spiral to be pulled out of the cable on each side of the damage for an almost unlimited distance?

Dr. T. Ingledow, and **Messrs. R. M. Fairfield, E. L. Davey, K. S. Brazier** and **J. N. Gibson** (*in reply*): The cable cost was approximately 40% of the total cost of the interconnector and 75% of the submarine section. The economy effected by using a smaller conductor for the submarine portion was considered to be outweighed by the importance of continuous lengths. The thermal resistivity of the sea bed was based on existing data.

The pre-impregnated dielectric was chosen because continuous manufacture was possible and there was no risk of choking the gas channels; also the permittivity of this type of dielectric is low, which is important for long-length a.c. installations.

The rigid joints were checked for gas tightness by vacuum testing before being lowered into the sea. Monel metal was used for the gastight enclosure because it is non-ferrous and has a high corrosion resistance and high mechanical strength. Aluminium alloy was used for the casing because of its lightness and high corrosion resistance.

The cable spacings in relation to the depth of water were such that any cable could be recovered without damaging another. The slightly higher reactances quoted for the closer-spaced cables probably arise from limitations of the Bosone formula which was used for the calculations. Measurements were not made.

A voltage of 10 kV can exist between the armour and the gas-retaining sheath when an impulse passes through the cable. The armour and gas-retaining sheath are bonded and earthed at each end. The circulating current in the sheath, reinforcement and armour amounts to 100% of the conductor current.

A separate sealing-end insulator was used for the gas connection to ensure that there was an adequate and safe gas feed for the very long lengths of cable, and this could be isolated for maintenance. The gas charges the space above the compound in the sealing end via a Neoprene 'leak gasket' on the underside of the plate forming the bottom of the dome, and when depressurizing, the gas in contact with the compound escapes via the gasket. The time to release the pressure on the system is not controlled by any difficulty with the compound in the sealing end but merely by the volume of the gas in the cable. The setting of the arc-gaps was somewhat higher than those on the overhead lines connected to the cable.

The sheath reinforcement used was the compensated type on which satisfactory experience with land cables has been available since 1937. Pressurizing of the cable tends to render it less flexible by forcing the sheath into contact with the reinforcing tapes, while subsequent handling will loosen the tapes so that the sheath distends further after re-pressurizing. These effects are cumulative, and limiting the number is therefore beneficial.

The insulation was reversed in order to reduce the torque on the conductor during lapping. The first reversal was made after 48 papers had been applied, so that the gas spaces at the reversal position are subjected to a lower electrical stress than that at the conductor surface. It is preferable electrically to apply paper tapes with the same direction of lay throughout, and the

practice adopted is a compromise to satisfy the electrical and mechanical requirements.

The low-pressure gas alarm was fixed at 250 lb/in^2, and the time taken for gas to pass through the 15-mile length was two hours.

For convenience, points of individual interest raised by speakers are answered as follows:

Mr. Bishop.—The economy achieved by using a stress of 100 kV/cm is limited by the charging-current effects. It was considered desirable, in view of the mechanical duty imposed by handling and laying, to increase the overall factor of safety of the cable by using the lower design stress of 85 kV/cm.

No final examination of the cable over the ridge off Galiano Island was made. We found that existing cable ships can quite easily be adapted for power-cable laying. The factory joint broke down at 640 kV impulse voltage.

Mr. Cundall.—The consulting engineers brought to bear on the project their broad knowledge and experience and critical faculties, which were of great benefit.

It was considered that aluminium sheathing could not be adapted to continuous-length manufacture. Furthermore, its stiffness would introduce undesirable complications in handling, coiling and laying.

Mr. Queen.—The zero-sequence impedance was approximately 1·32 ohms per mile of 3-phase link. The cables are solidly bonded and earthed at each end of the run, and the maximum earth-fault current is roughly 20 000 amp, calculated on the assumption that there is a fault at the mainland end of the long length.

The cables are not used as part of a telephone communication system.

The lead press used was the Glover tray type, which produces a sheath with no weld weakness, while the recharging times are limited sufficiently to avoid risk of damage to the paper insulation.

The effects of air and humidity entrained in a joint are negligible and no precautions are necessary. When cutting the cable with an explosive grapnel the latter is destroyed. No drying out of the cable is necessary during fault-clearance operations.

Mr. Peters.—The question of shedding load to resynchronize after a fault has been resolved by the installation of a second circuit in July, 1958. One circuit of three cables and a spare was originally planned. The fifth cable was eventually included as a further standby in view of the importance of supply continuity, the pioneering nature of the project, and the fact that, if successful, a double circuit of seven cables would be installed. No problem has arisen owing to the high charging current, even at times of light load.

The jute serving over the armour is required during manufacture and installation to prevent 'bird caging' during coiling, and is ineffective once the cable has been laid. Past experience has shown that the armour wires are satisfactory from the abrasion and corrosion aspects while in direct contact with the sea water.

Mr. Wallace.—After a repair the extra length of cable would be laid out in the form of a bight on the sea bed to avoid any tendency to kink. Bronze armouring was considered but was ruled out on the score of cost.

Mr. Mather.—In the event of damage to the cable the gas pressure can be maintained indefinitely by feeding in gas at the ends to prevent ingress of water to the installation. In the case of a cable sustaining damage in two places, it would probably have to be cut and the position of the leak in each section located separately.

Mr. Roscoe.—The reactance between the various cores does not affect the carrying capacity of the cable.

Mr. Hastie.—The cable dielectric was designed in accordance with the Beaver–Davey patent. We have stated that it is unsatisfactory to leave the screened cable exposed to the atmosphere for many weeks, and actually the safe time of exposure is of the order of days. The lapping machine is enclosed, so that, in the case of breakdown necessitating several hours of stoppage, the whole enclosure can be reduced to a very low humidity. The paper tapes between the lapping heads and the cable are exposed in single-thickness form, which is the worst condition for pick-up of moisture. No control of the atmosphere in contact with the cable is necessary once the unperforated overlapped copper tape screening has been applied. The use of a small press results in more uniform temperature conditions owing to the more frequent but shorter-time recharging stops. Stop marks are of similar quality to the sheath itself.

Mr. Henderson.—On the reconstituted joint the pipe is swaged down tightly on to the cable over the whole length, so that there is no clearance between the pipe and the cable. No difficulty was encountered owing to the cable pressure on the bottom turns. Exhaustive tests were taken initially on this aspect. The vulcanized-rubber sheath was fully cured after three minutes.

A d.c. transmission would not have been economic for a one-way transmission project of this power and distance. On the cross-Channel link a d.c. system has the technical advantage that the control of flow of power is independent of the frequency.

Mr. Marshall.—The lead-sheath thickness was checked every two hours. The variations did not exceed 10 mils, and they were corrected by the use of an adjustable nut. The optimum armour lay of 12 times the pitch-circle diameter was based on coiling, bending and actual sea-trial experiments in which kinks were produced. The sheath shrinkage was based on ensuring that along the whole length of cable it was definitely compressing the dielectric at the minimum-diameter sections.

Mr. Pimble.—The load growth was due partly to industrial and partly to domestic demands. All the cables are employed in turn for the actual circuits. The reason behind the choice of telephone exchanges in preference to supervisory equipment is fully dealt with in a paper by Wilkinson and Rohrmayer.*

The test arrangements are provided at the terminals, but since the cables are used in turn, no routine tests are carried out. The cables can be isolated from the overhead lines.

Mr. Palmer.—Cable manufacture in one long continuous length is impossible with all but the type chosen, because of impregnation difficulties. The cable lengths are limited on account of the size of the impregnating vessels.

The immersed-weight/diameter ratio of the power cable is so much higher than that of telecommunication cables that there is no risk of movement anywhere along the routes under tidal action. On the shore ends, articulated cable protectors were used for mechanical protection.

For the installation in question the external armour was necessary for mechanical protection of the cable. Kinking was virtually eliminated by applying the reinforcement opposite hand to the armour.

Mr. Tompsett.—Six cables similar to those described in the paper would carry approximately 1 GW of power if operated as three d.c. circuits. We agree that a d.c. submarine cable transmission requires less space than an a.c. scheme, but the scheme must be sufficiently large and extensive to justify the capital cost involved by the use of the d.c. equipment.

Mr. New.—When the cable is cut under water the gas pressure falls to that of the external water. It is essential, when the pressure has fallen to the low-tide value, that the gas feed shall be sufficiently rapid to ensure that the internal gas pressure

* WILKINSON, S. B., and ROHRMAYER, A.: 'Relay Protection and Control of the 132 kV Underwater Cable Tie between Vancouver Island and the B.C. Mainland', *Transactions of the American I.E.E.*, Paper No. 57/670 presented June 24–28th, 1957.

is always above that of the rising-tide value. The initial differential of 35 lb/in^2 is ample. The installation will be maintained for two to four weeks by the gas supply on site. Gas-leak location would probably take several days. We agree that grappling the cable in the right place might present some difficulties in practice.

An extensive programme of tests had established the performance of the lead press and the operating, instrumentation and other control requirements to ensure that the quality and uniformity of the sheath were of the high standard required.

Mr. Rees.—When the conductor of a submarine cable is heated, excess expansion occurs in the conductor relative to the sheath, reinforcement and armour. This is accommodated by an increase in the pitch circle of the strand wires, which should not exceed approximately 1% at the strand surface to avoid bursting of the metallized papers. To achieve this, the stranding lays were made somewhat shorter than normal.

Mr. Steel.—No account was taken of the diversity between the load on the mainland and Vancouver Island when preparing the scheme.

Mr. Archer.—The final decision on submarine cables was made in February, 1954, when the order was placed. Extra cable allowed on the long lengths was used as maintenance cable. The agreement between the estimated and actual length installed was within 2–3%.

The essential difference between the original Beaver–Davey gas-filled cable and cable used in the scheme was that, with the former, the sheath was loose and the gas passed down the annulus under the sheath, whereas, in the latter, the sheath was tightly applied and the gas passed down the hollow conductor.

Approximately 50% of the combined sheath, reinforcement and armour losses are in the armour. Without the armour, the sheath and reinforcement losses would have been 92% of the total losses due to the wide spacing of the cables. Rubber is considered superior to p.v.c. as an anti-corrosion protection, since it is more elastic and is a better mechanical protection against vibration.

Mr. Fricke.—The scow method was preferred to the floating-drum method because of the dog-legged approaches at the three island terminals, while, on the mainland terminal at Tsawwassen Beach, the cable had to be pulled up a 180 ft cliff after landing.

The reciprocating ram press is considered superior to the continuous screw press for extending alloy 'E' sheathing in long continuous lengths involving 600 hours' or more duration of extrusion.

Mr. Tolley.—No movement of the cables should occur under the effects of tidal currents since the immersed-weight/diameter ratio of the cable is relatively high. Experience has shown that, with a cracked or split sheath, no water ingress whatever occurs on a gas-filled cable over a period of months. A cable ship would be required for a repair in the Georgia Strait.

Mr. Davidson.—No trouble of any sort has occurred up to August, 1958. With the cable being cut under water, a positive gas flow ensures that no appreciable water ingress can occur.

Mr. Addenbrooke.—The cable routes are marked on navigational charts. Only one minor case of installation difficulty was encountered because of lack of complete control of the waters.

Mr. Shaw.—A pressure of 10 lb/in^2 (gauge) was kept on the cables during laying until the landed ends were opened for terminating. Serious damage to the sheath during laying might have resulted in the loss of a considerable length of cable. The normal methods, i.e. welding, were used to joint the copper and steel strands.

Mr. York.—Greater confidence has been gained since the laying of the first circuit.

Mr. Holttum.—The compensated reinforcement design, and also certain modifications on the scow method of landing, arose from the sea trials. The use of reversed-lay double-wire armour would result in a loss of flexibility of the cable. The gradient in the tunnel at the Tsawwassen termination was approximately 1 in 2½. The cable racks were spaced at 8 ft intervals, and the cables are clamped in each rack.

Mr. Fuller.—The transmission from the mainland to Vancouver Island involved two submarine sections, whereas a transmission from the Bonneville Power Administration would involve many sections. One case of interference by a local fisherman occurred during the laying operation.

The September and October figures in Table 4 were boosted by energy transferred to the British Columbia Power Commission at Stratford, while the November and December figures were reduced since half the energy was transferred back to the B.C.E. Co.

Mr. Harland.—The central spiral steel duct has a very low tensile strength indeed, and there is no possibility of its being pulled out of the cable at each side of the damage for any appreciable distance.

DISCUSSION ON 'D.C. WINDER DRIVES USING MERCURY-ARC RECTIFIER/INVERTERS'*

Before the North Staffordshire Sub-Centre *at* Hanley, *3rd March, and the* South-East Scotland Sub-Centre *at* Edinburgh, *1st April*, 1958.

Mr. T. Storrs (*at Hanley*): The authors state that the efficiency of a rectifier drive is considerably greater than that of either a.c. or Ward Leonard drives; case 4 in Table 2 approximates our Hem Heath Koepe winder, and the power consumption of the Ward Leonard set is 103% compared with 100% for the rectifier winder. The authors also mention that on larger units it may be necessary to install temperature-control equipment and substation ventilation auxiliaries. Would these considerations show much variance of the percentage figures quoted, and in view of the lower power factor of the rectifier winders and probably resultant higher maximum demand, would the cost per wind—which is more important than the power per wind—be less favourable for the rectifier winder?

The comparative power consumptions shown in Table 2 cover large rectifier units, and to my knowledge the only installation in this country is the 350 h.p. Monk Bretton winder; do the figures obtained in practice support those given in the paper, which are presumably calculated ones?

I cannot understand the reference to acceleration limit in Section 5.2.4. In a good closed-loop system the control circuit should be such that the cam-gear reference or the movement of the driver's lever will always prevent the natural deceleration

* Abram, L., McBreen, J. P., and Sherlock, J.: *Proceedings I.E.E.*, Paper No. 2324 U, February, 1957 (see 105 A, p. 77).

from taking charge. If the natural retardation is too great, it is obvious that the power will be required to control the winder to correct retardation, and this makes it all the more important that the change-over from power to braking and vice versa is carried out as quickly and as smoothly as possible. I should like the authors' comments on this feature of the Monk Bretton winder. Do they think that the installation is considered a good closed-loop system with good acceleration and retardation control?

Which type of rectifier installation would be used on units of, say, 2 500 h.p.? Would it be on a large single rectifier or a bank of smaller rectifiers? What would be the effect of a backfire occurring in either case, and should simultaneously an emergency trip occur, would regenerative braking be available? Since on the larger winder units this would be effected by first weakening the field to zero and then increasing it in the opposite direction, would the tendency of the winder motor to accelerate under these conditions aggravate the conditions which initiated the primary trip?

Finally, why was the Monk Bretton winder supplied at 3·3 kV instead of direct from the 11 kV supply? Is there any inference that on large winder installations mercury-arc rectifiers could not be used on higher voltages, with possible saving of double transformation losses and additional capital outlay?

Mr. D. B. Russell (*at Hanley*): The authors state that for good control the winder must have adequate speed of response. I presume this refers to torque response, since the speed response would be limited by the acceleration control. If no acceleration control were present, the speed response would depend upon the torque available from the motor, the size of which is determined by the winder duty and is sufficient to supply the acceleration and retardation peaks. The speed response available will therefore depend upon these factors. Is it suggested that the motor size might have to be increased to obtain the required speed response?

In seeking to advance the use of rectifier-controlled winders, the authors have over emphasized the disadvantages of a.c. winders. The control gear for an a.c. winder is no more than that required for a rectifier scheme, and the present restricted torque range of the former could be improved by suitable liquid-controller design.

Mr. L. Goodall (*at Hanley*): The paper deals in detail with a 300 h.p. winder, but winders of 6–8 times this size may have to be considered. The paper, however, gives information which indicates the effects which may arise with larger winders. While a 2 500 h.p. motor supplied from a 6·6 or 11 kV system may not present undue difficulties when starting, say, once per day, the problem is entirely different when such a motor is started once per minute, since the voltage drop cannot be corrected by automatic voltage control. Such conditions will usually necessitate a 33 kV supply. With Ward Leonard starting the current demand from the supply increases gradually, because of the relatively slow building up of the generator field during acceleration, and the power taken is proportionate to generator voltage. It is assumed that, when supply is through a rectifier, the full starting power will be taken immediately and therefore cause more violent fluctuation.

With rectifier winders further difficulty will be introduced by the harmonics. This may be expected to result in increased iron losses in transformers, overloading of power-factor-improvement capacitors and possibly television interference. From the figures given in Table 3 and considering a motor taking 2 MVA from a typical 6·6 kV supply through a 6-phase rectifier, it is estimated that the harmonic voltages produced might result in as much as 30% overload in any capacitors connected to the system. Is it therefore contemplated that a 33 kV supply and at least 12-phase rectification will be provided for all large winders? Television interference has been caused by 1·5 MW of ordinary rectifier load on a 6·6 kV system with a short-circuit value of about 40 MVA.

I consider the second sentence of Section 7 is very important, and that where rectifier winders are to be installed the problems arising should be discussed jointly at the earliest possible stage by representatives of users, manufacturers and the supply authority.

Mr. A. Gavrilović (*at Hanley*): In Section 4.4.1 of the paper as presented at the meetings the authors obtained the following results for the peak inversion at twice full load with the supply voltage 20% low: $\beta = 39{\cdot}5°$, $u = 21°$ and $\delta = 18°$. During the discussion at Manchester* I pointed out that at twice full load the effective reactance was 18%, giving $u = 21°$, and if the commutating voltage were simultaneously 20% low, the reactance would be 22·5% and u would be 34°, leaving only 5·5° for deionizing. This part of my contribution, which was omitted after the paper had been modified, was followed by a question on how the deionizing time was measured, since I doubted whether a power convertor at twice full load would, in fact, deionize in less than 5°. Mr. Hammond also pointed out (p. 94) that the authors had failed to allow for an increase of effective reactance when the supply voltage was reduced. The authors subsequently modified their calculation, but, in order to obtain sufficient deionizing time, claimed safe inverter operation only down to 85% supply voltage; and since they did not indicate that Section 4.3.1 had been rewritten, both Mr. Hammond's remarks and mine need clarification.

In everyday design the overlap is calculated when estimating the power factor, which is done at normal supply voltage. A transient increase of overlap has no effect on rectifier operation, but may cause maloperation of an inverter. This is the reason why a rectifier engineer may make this mistake when considering the inverter operation for the first time.

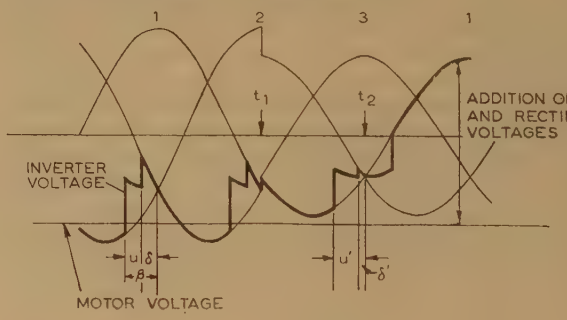


Fig. B

In Fig. B it has been assumed that, owing to transient reduction of supply voltage at t_1, the overlap, u', was so large that the convertor failed to deionize in time δ', and anode 1 therefore picked up current again at time t_2, and 'followed through' into the rectification region; a short-circuit thus resulted. It is clear that even a voltage reduction for only a cycle or two can result in this inverter maloperation.

The method of calculating the deionizing margin by having to calculate both β and u is cumbersome and can lead to mistakes. The following equation, giving δ directly, can be obtained:

$$\cos \delta = \frac{V_m + y(V_x - V_r) - V_a}{xV_{d0}}$$

where V_m = Motor voltage.
V_{d0} = Convertor theoretical no-load direct voltage.
x = Fraction of the instantaneous supply voltage.

* *Proceedings I.E.E.*, 1958, 105 A, p. 89.

δ = Deionizing margin.
V_x = Reactive voltage drop at full load.
V_r = Resistive voltage drop at full load.
y = Fraction of direct load current.
V_a = Arc drop.

From the data given Section 4.3.1 for twice full load and the supply voltage 15% low we obtain

$$\cos \delta = \frac{500 + (29\text{–}12) \times 2 - 22}{643 \times 0{\cdot}85}$$

$$= 0{\cdot}938$$

so that $\delta = 20{\cdot}3°$

This method of calculating the deionizing margin is shorter and safer than the indirect method normally employed.

Mr. O. L. Robson (*at Edinburgh*): The general requirements of winder control set out in Section 2.4 impose somewhat severe limitations, but these are functions of the control system rather than of the power source; and since these have been met over many years with the older forms of drive, there should be no serious difficulty in meeting them with the rectifier/inverter drive.

The arguments put forward in Section 3.3 in favour of rectifier drives, namely no special foundations, static equipment requiring little maintenance, reduced dimensions, higher efficiency and therefore less heat to be dissipated, are well known and are not peculiar to winder drives, but nevertheless are very important in this particular application. If there were no compensating disadvantages—and it may be that the authors consider that this is the case—there would be no question but that the rectifier/inverter was the correct type of equipment to adopt for winder drives to the exclusion of all others.

It is obvious that, from the economic aspect the figure-8 connection cannot be considered in comparison with the figure-0 connection; but it is unfortunate that the use of the latter necessitates either armature switching or field reversal of the motor. In armature switching it is obvious that one contactor must open before the other closes, and yet the time during which the winder is running free must be minimized. Is it necessary to use special high-speed contactors on this account, and what do the authors consider the maximum time for which this free running can be tolerated?

In Section 4.3.3 I am sorry to see the authors referring to a triple-star connection instead of using the nomenclature of B.S. 1698, which is also used by the I.E.C., namely fork connection. This is particularly unfortunate, since reference is then made to double-star connection, which certainly does not bear any two-thirds relationship to the so-called 'triple-star'. The fork connection, although not used as frequently as the double-star, is in quite general use for rectifier transformers, and is in no way less conventional than the latter.

In Section 4.4.3 the authors state that 'in the case of backfires, both the a.c. and the d.c. protection must function rapidly enough . . . to prevent any undue gassing in the rectifier, which would cause permanent damage'. While this is true of the pumpless rectifier, the pumped type—which seems to be generally out of favour in this country—is not permanently damaged by excessive gassing, and is quickly restored to condition by the operation of the vacuum pumps.

In Section 4.4.4 it is recommended that the ambient temperature be controlled above a minimum value of 15–20° C. Surely, if the authors are seriously laying down a recommendation for a minimum temperature, it would be better to be more explicit and not to give a margin of 5° C. While I agree that a temperature of this order is advisable, it must be remembered that Appendix A of B.S. 1698 states that an equipment shall be capable of carrying rated current immediately on starting with all accessible parts at a temperature of not less than 10° C.

Section 5, dealing with the control circuit, seems to be the crux of the whole installation. Is this system of control a novel one or have similar systems been used in the past with other forms of winder drive?

I am pleased to note the very satisfactory results given in Section 6.3. The distorted load currents taken from the supply by rectifiers, even of the free-firing type, have frequently been blamed for troubles experienced on supply systems, and the negligible effect which this equipment has had on the supply is very gratifying.

Messrs. L. Abram, J. P. McBreen and **J. Sherlock** (*in reply*): We propose to reply by subject rather than to deal with each speaker individually.

Comparison between rectifier, a.c. and Ward Leonard drives.—The figures shown in the paper are calculated ones, and no data are yet available to indicate the power consumption obtained in practice. In arriving at these calculated figures, account has been taken of all the auxiliaries required for the different types of drive. The effect of temperature-control equipment is negligible, since heater losses will be less than 0·25% of the total power consumed by the winder.

Number of phases and peak loading on a.c. system.—With a.c. and rectifier drives the maximum current is drawn from the supply system at the start of the wind, while for a Ward Leonard drive it builds up as the winder speed rises. In any particular installation, this fact, as well as the frequency with which the load is imposed on the system and the permissible voltage regulation, is taken into account when determining the point in the supply system to which the load is to be connected.

The Monk Bretton installation was supplied at 3·3 kV because of the nature of the distribution system at the colliery. There is no reason why larger installations cannot be supplied at higher voltages, and it is possible to reduce transformation losses and additional capital outlay by so doing.

In rectifier installations, consideration must also be given to the effect of harmonics introduced by the load. In the latter connection, the C.E.A. Recommendation, 'Harmonic Distortion caused by Mercury Arc Rectifiers', would indicate that, for the 40 MVA system quoted by Mr. Goodall, the maximum rectifier load to minimize interference would be 200 kW for 6-phase operation or 750 kW for 12-phase operation.

Backfiring.—In the event of a backfire the a.c. and d.c. protection is expected to come into operation and to produce a primary trip on the winder. The effect of this is to remove all electrical control from the winder and to bring it to rest by means of the mechanical brakes. Under these conditions, regeneration in the normally accepted sense is not available and there is no tendency for the winder speed to increase.

Temperature control.—The operating conditions for winder drives is very different from that encountered in previous rectifier applications, and it is doubtful whether B.S. 1698 was intended to cover such applications. We are of the opinion that 10° C is too low a starting temperature for winding and similar duties, and a higher value is desirable depending on the rectifier design.

Type of rectifier.—All rectifiers, whether pumped or pumpless, must have a permissible fault limit, whether it be imposed by considerations of gassing or of mechanical damage. We do not feel that there would be any advantage gained by using pumped rectifiers, since the fault limit is of the same order as for a similarly rated pumpless unit, while additional complication is introduced by the vacuum pumps which must be employed.

Acceleration limit.—The system of acceleration and retardation limiting applied at Monk Bretton has the disadvantage that

acceleration can be limited only if positive torque is required, and retardation if negative torque is required, from the winder motor. In this respect it is inferior to that obtainable from a Ward Leonard system. It is for this reason that in Section 5.2.4 we suggested that these limits be provided by controlling the rate at which the speed reference can change.

Control system.—The requirements set out in Section 2.4 are, in our opinion, the minimum necessary for a satisfactory closed-loop control system. The system employed at Monk Bretton is similar in principle to others which have been used on Ward Leonard winders, but there are differences in detail. It is correct that rapid response of torque is required, since the acceleration limit imposes a limit on the speed response, and without acceleration limit it is undesirable to increase the motor size above that required by the winding duty.

General.—The system described in the paper is being employed on larger installations. In such cases a number of 6-anode rectifier tanks are being employed and the transformer connections are so arranged as to give 12- or 24-phase operation as required. In all cases it is necessary to consider both the advantages and the disadvantages of all three types of drive before deciding which is the most suitable for the particular installation.

We agree with Mr. Robson's comments regarding nomenclature, and we would like to thank Mr. Gavrilović for the suggested combinations of eqns. (2) and (7*b*) from Reference 8 to obtain the deionization angle.

MECHANICAL STRENGTH OF POWER TRANSFORMERS IN SERVICE

CORRECTION TO THE DISCUSSION

It is regretted that Figs. B and C were omitted from Mr. Allen's contribution to the discussion on Mr. Norris's paper on page 632 of Vol. 105 A (December, 1958). The contribution is printed below in full.

Mr. P. H. G. Allen (*at Rugby*): I was pleased to note that, in his reply to the London discussion, the author refuted a suggestion that he had confined his treatment to disc windings because of any superiority of this type of winding over the layer type for high-voltage use. The magnetic design of the layer-type winding is, however, complicated by some of those factors which contribute to its excellent electrical performance. Boyajian has remarked* that 'the freedom of the transformer designer to use the most economical or convenient winding arrangement in meeting a particular requirement is handicapped by his inability to calculate reliably (and with a reasonable amount of labour) the reactances and forces of those winding arrangements which depart considerably from certain simple symmetrical types and proportions'. We have therefore been studying the use of the electrolytic-tank analogue to map the leakage magnetic field. A brief description of our technique has been published,* and we hope that fuller details will be available in due course. Fig. B shows the type of flux plot that can be obtained making the usual assumptions. It is a straightforward case used purely as an example. Flux quantities are referred to the total leakage flux, which here passes between the inner and outer turns at the centre plane. Measurement of the potentials assumed by each electrode gives most information. For example, in the case of force calculations, we plot these potentials against distance along any layer, as shown for the outer layer in Fig. C. From the slope of this curve at any point can be derived the radial component of flux density which is needed for force and eddy-current-loss calculations.

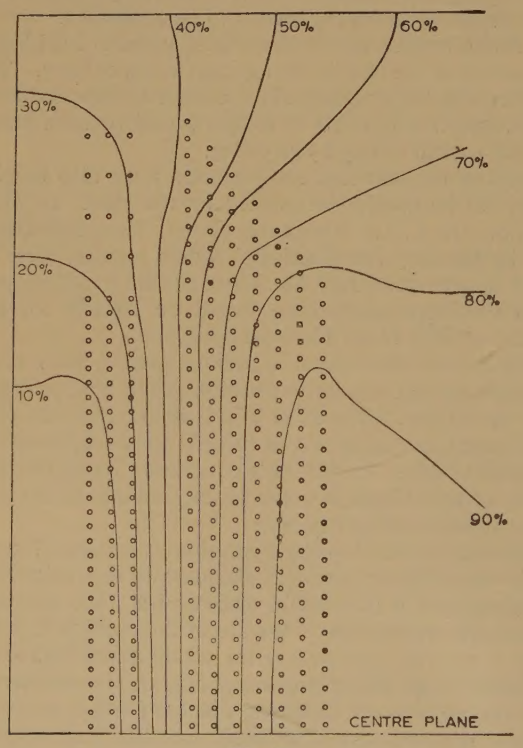


Fig. B

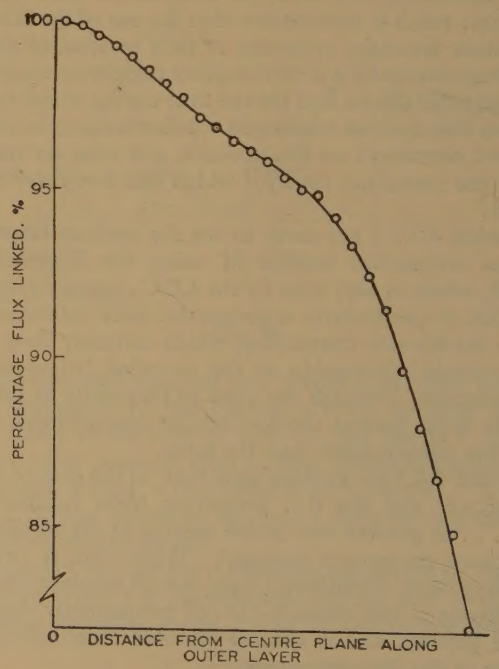


Fig. C

* BOYAJIAN, A.: 'Leakage Reactance of Irregular Distributions of Transformer Windings by the Method of Double Fourier Series', *Transactions of the American I.E.E.*, 1954, Part III, p. 1078.

* ALLEN, P. H. G., and FOSTER, J. H.: 'Transformer Magnetic Field Plotting by Electrolytic Tank', *Review of Scientific Instruments*, 1957, 28, p. 1095.

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, FEBRUARY 1959

CONTENTS

		PAGE
The President's Inaugural Address	S. E. GOODALL, M.Sc.(Eng.), F.Q.M.C.	1
Measurement and Control Section: Chairman's Address	J. K. WEBB, M.Sc.(Eng.), B.Sc.Tech.	11
Supply Section: Chairman's Address	D. P. SAYERS, B.Sc.	16
Utilization Section: Chairman's Address	R. A. MARRYAT, B.Sc.(Eng.)	21
Centre, Sub-Centre and Group Chairmen's Addresses		26
The Objective for Euratom (Supply Section Lecture)	PROF. F. GIORDANI	41
A New Method of determining Rotor Leakage Reactance and Resistance of a Three-Phase Induction Motor	PROF. M. V. DESHPANDE, B.E., M.S., and T. R. SUBRAHMANYAN, B.E., M.E.	46
The Application of Transistors to Phase-Comparison Carrier Protection	COLIN ADAMSON, M.Sc.(Eng.), and E. A. TALKHAN, B.Sc., Ph.D.	51
Discussion on 'Power System Protection, with particular reference to the Application of Junction Transistors to Distance Relays' and 'A Dual-Comparator Mho-Type Distance Relay Utilizing Transistors'		64
Discussion on 'British Columbia–Vancouver Island 138 kV Submarine Power Cable'		66
Discussion on 'D.C. Winder Drives using Mercury-Arc Rectifier/Inverters'		73
Correction to discussion on 'Mechanical Strength of Power Transformers in Service'		76

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Example.—SMITH, J.: 'Overhead Transmission Systems', *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

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